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AUTOMATIC PROTECTION OF A.C. CIRCUITS

by

G. W. STUBBINGS

B.Sc., F.Inst.P., A.M.I.E.E.

THIRD EDITION

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PREFACE

In this book I have endeavoured to deal with the subject of automatic protection in a logical manner, by devoting a considerable amount of space to a discussion of the theory of protective transformers and their interconnection and to the theory of protective relays before dealing in detail with modern protective circuits. It is thought that such a preliminary study of the components of protective gear will not only enable the reader to understand more readily the operation of the practical methods of automatic protection thereafter described, but will also put him in a position of being able critically to assess the value of new methods of protection which are from time to time put forward.

The subject matter of the book falls into five main divisions; protective transformers, the interconnection of these transformers to form protective circuits, relays, modern methods of protecting electrical machinery and transmission networks, and, finally, the testing of relays and protective circuits. Under the heading of transformer interconnection may be included a study of the theory of symmetrical components.

I have added, as appendices, a glossary of technical terms, and a short bibliography. The books and papers mentioned in the bibliography have been of material assistance to me in the preparation of this work, and they can be recommended to the student who desires to pursue his reading in this subject.

PREFACE TO SECOND EDITION

In this edition I have corrected some errors, kindly pointed out by correspondents, and I have included some additional matter relating principally to instrument transformers, busbar protection, testing and maintenance, and to negative sequence relays and their applications. I am indebted to the Metropolitan-Vickers Electrical Co., Ltd., for technical particulars of such of their relays as are described herein.

PREFACE TO THIRD EDITION

In this edition I have added some matter on the interconnection of current and voltage transformers and the phenomenum of what is called neutral inversion, on the protection of machines and cables, and on relay maintenance. I have also added to the Bibliography references to the most important of the many highly-technical papers on automatic protection that have appeared since the last issue of this book.

G. W. STUBBINGS.

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THE DEVELOPMENT OF AUTOMATIC PROTECTIVE GEAR

A COMPLETE system for the supply of electrical energy to private consumers comprises generating, transforming and converting plant, together with transmission mains and consuming devices. Each of these components, considered as a conductor, is rated to carry a more or less definite maximum current, which is fixed by the consideration that the maximum temperature attainable with this current flowing must be consistent with safe operation. If this rated maximum current is exceeded, a condition will be set up in which there is a tendency for the conductor carrying the current to reach a temperature beyond the safe limit. Due to the fact that a conductor of electricity necessarily possesses some thermal capacity, the temperature resulting from the incidence of a current in excess of the rated maximum value will depend upon the magnitude of the excess and upon the time during which it persists. An excess current may arise from an inordinate, but otherwise normal use of the supply. A familiar example of this cause of excess current is that of the mechanical overloading of a motor, and, as a matter of fact, excess currents arising from causes such as this are usually known as overloads. Excessive currents in a circuit may also arise from a failure of insulation. If this failure is that of the insulation of two of the supply mains between which there is a nominal potential difference, the condition is called a short-circuit. If the failure is that of the insulation between a conductor and earth, the condition is known as an earth fault. The current resulting from a short-circuit is generally, but not invariably, much greater than one resulting from an overload. The current in an earth fault may be of the same order as that in a short-circuit, if *one point of the supply* system is joined to earth by means of a connection of negligible resistance. If, as is sometimes the case, the connection to earth contains an appreciable resistance, the current in the earth fault will be limited. The magnitude of the current in a short-circuit is determined solely by the characteristics of the generating plant and of the conductors between this plant and the short-circuit. It is thus possible for a short-circuit on the installation of a consumer taking a small supply, to give rise to a very large fault current, if this installation is adjacent to a source of supply with a large capacity of plant.

From the earliest beginnings of electricity supply the efforts of engineers have been directed to the problem of the automatic isolation of circuits in which, due either to overloads or short-circuit or earth faults, an excessive current is flowing. The first device to be used for this purpose was the fuse. The well-known limitations of fuses led to the development of the air-break circuit-breaker for the interruption of short-circuit currents too great to be dealt with by fuses. These two devices are still largely used for low-pressure circuits, and during recent years their respective spheres of application have been enlarged by the development of the small circuit-breaker to displace fuses in consumers' installation, and by the revival of oil-immersed fuses for use in extra-high-tension A.C. circuits.

The development of power transmission and distribution to transforming centres by alternating current at high voltages occasioned fresh circumstances and raised new problems in respect to the isolation of faulty circuits. The troubles experienced with fuses in high-pressure circuits led to the exclusive use of the oil circuit-breaker, and this, combined with the necessity for the employment of current transformers for the measurement of current in such circuits, and with the development of electrical remote control of switchgear, led to the use of relays in which the effect of an abnormal current in the main circuit is to close a local circuit and to trip the associated circuit-breaker electrically

The concentration of increasingly large amounts of generating plant in single power stations led to a progressive increase in the possible magnitude of short-circuit currents, and intensified the necessity for the rapid isolation of faulty components of the system, not only on account of the destructive effects of the excessive currents, but also to avoid the disturbance to the operation of rotating plant which results from anything but a transient fall in voltage. Finally, the increase in the capacity of transforming centres called for the provision of more than one supply line, by parallel feeders, interconnectors, and ring mains, and the urgent demand for continuity of supply at these transforming centres led to the requirement of what is known as the discriminating property of apparatus for the isolation of faulty circuits, whereby the shortest section of a distributing network containing a fault would be disconnected at each end from the remainder of the system by means of the appropriate apparatus, while similar apparatus, associated with normal sections, would remain unaffected, notwithstanding these sections might be carrying part of the excessive current in the short-circuit.

The apparatus for the isolation of faulty components of a supply system is usually known in the aggregate as protective gear. This apparatus has now reached a high state of development, and to its excellence is due in a large measure the high degree of continuity of supply enjoyed by consumers of electrical energy.

The Development of Discriminating Protective Gear.

We have already alluded to the need for discriminating protective gear which arose when sub-stations and transforming centres were fed from two or more distributing mains. The development of protective gear possessing this characteristic has proceeded along four distinct lines. The earliest and simplest method of obtaining discriminating action in protective gear is by the use of graded time-lags. When this method is employed, the relays, carrying a secondary copy of the line current furnished by current transformers, are designed to close the contacts in the auxiliary tripping circuit after the lapse of a time interval from the commencement of operation. In some relays this time-lag is independent of the current, in others it is an inverse function of the current. The basic feature of the relays is that the nominal time-lags are adjustable, and that if two relays carry the same current, the time of operation of the one having the smaller nominal time-lag will, for any value of the current, be less than that of the one having the greater nominal lag. The application of relays of this type to an open-ended main feeding a number of transforming centres is readily understood. The outgoing main at each centre is controlled by an oil circuit-breaker and relay, and the nominal time-lags of the relays diminish by one stage as each sub-station is passed. A fault in the feeding main will cause the tripping of the circuit-breaker at the next sub-station nearest to the source of supply. This system of protection cannot give complete discrimination, as all sub-stations on the side of the fault remote from the power station will lose their supply.

Furthermore, the method suffers from the disadvantage that the time-lag between the incidence of a fault and its isolation increases, the nearer the fault is to the source of supply. The severest faults are thus those which remain the longest on the network.

The simple system of graded time-lags outlined above is suitable only for circumstances in which each sub-station has but one feeding main. If a ring main is used, so that a series of sub-stations are each fed by two mains, a faulty section of the ring main must be disconnected at the sub-stations at each end of the section, while all circuit-breakers controlling other sections must be unaffected. This requirement can be satisfied by the use of relays which, ~~in addition to an adjustable time-~~lag, have the property of being operative only when the power flow is in a definite direction. The application of relays having these characteristics will be described later, and it will be then seen that, within limits, the use of relays with graded time-lags and which are responsive only to power flow in a definite direction, will enable discriminating protection to be obtained in a system in which each sub-station is supplied by two or more feeding cables. This system of protection suffers from the same disadvantage as that employing non-directional graded time-lag relays for open-ended feeders. The use of A.C. directional relays on three-phase systems is also attended with certain difficulties, which will be explained in due course, and which have only been satisfactorily overcome during recent years.

The first advance along the second line of development of discriminating protective gear was made by Price, in the invention of what is now usually known as leakage protection.

The outstanding feature of this scheme is that current only appears in the relay on the occurrence of an earth fault, and that, during normal conditions or conditions of overload, the relay current is negligible. This feature is in marked contrast to that of the methods previously outlined, in which the criterion for relay operation is that the relay current should be considerably in excess of the normal value. With the leakage system of protection relatively sensitive settings can be used, and although this method did not, in itself, give discrimination for interconnected systems, it enabled earth faults on open-ended circuits to be cleared with certainty and rapidity.

The invention of the leakage system of protection pointed the way to the next great advance, which solved the problem, from the point of view of basic principle, of securing the instant disconnection of a faulty section of a ring main or other interconnected distributing system. The principle underlying all the modifications of the original Merz-Price system of protection is that in a conductor which transmits electrical energy from one point to another, the current entering one end of the conductor is, in normal conditions, exactly equal to that leaving the other, and that this equality will be disturbed if energy leaves the conductor at some point due to a fault. This principle is applied very simply by comparing the secondary currents or voltages of two current transformers, one at each end of the conductor, the electrical communication between the two transformer secondary windings being established by means of pilot wires.

With this method of protection, current only appears in the relays controlling the circuit-breakers of any section of a distribution network when there is a fault in the section. The breakers of non-faulty sections will be unaffected because, notwithstanding the current transformers in these sections may carry current which is feeding into the fault, the magnitudes of the current at each end of the section will be the same, and the relays, being responsive only to a difference in these currents, will be free from any tendency to operate. The Merz-Price system, although simple in principle, is subject to several limitations, the overcoming of which received the constant attention of engineers for many years. The chief of these limitations is that the secondary voltages or currents of current transformers carrying equal primary currents are liable to diverge from equality when the primary current is very large in relation to the rated maximum value. This tendency led to the operation of relays controlling the circuit-breakers of non-faulty sections of a network when heavy currents passed through these sections to the fault. These limitations, together with the methods by which they have been overcome, will be dealt with hereafter, and it will suffice at this stage to note that the Merz-Price was not only the first method of obtaining instantaneous discriminating protection for an interconnected distributing system, but it is the basis of a large number of modern protective systems now in successful operation.

The third line of development of discriminating protection was based upon the fact that when current is conveyed from one point to another along two paths of equal impedance, this current will divide into two equal components. This principle is applied in the split-conductor system associated with the names of Merz and Hunter, in which each line current in a three-phase cable is carried by two conductors, of equal cross-section, insulated from each other. The currents in the two parallel conductors are passed at each end of the cable through the core of a current transformer in opposite directions, so that, when these currents are equal, their resultant magnetic effect is zero. If a fault occurs in a cable of this type, the balance of the currents in the two parallel conductors of at least one phase will be upset, so that a resultant magnetic effect will be produced in the core of a current transformer which will give rise to a current in the associated relay. This system of protection, like the Merz-Price system, is completely discriminating, and is instantaneous in action.

A number of other systems of protection have been devised which, although differing in basic principle from the split-conductor system, are like it in employing cables of special construction. These have found limited application and will be mentioned in due course.

The final step in the development of automatic protective gear was taken with a view to the avoidance of the high capital costs of pilot wires or special cables, which formed one of the principal economic drawbacks of those systems of protection normal and fault conditions, and with their interconnection in the various ways required for automatic protection. The theory, construction, and operating characteristics of the various classes of protective relays will next be considered. Finally we shall deal with the assembly of protective transformers and relays in the various manners for the protection of electrical machinery and cable networks.

CHAPTER II

PROTECTIVE TRANSFORMERS

General Remarks on Protective Transformers.—The functions of current and voltage transformers used as components of protective gear are similar to those of instrument transformers, and consist in the furnishing of a current or voltage proportional to and in phase with the current or voltage in the main circuit to which the protective relays are required to be responsive. Till recent times the secondary current of a current transformer was invariably five amperes with the rated primary current flowing. For reasons which will be explained hereafter, many protective current transformers are now so designed that the rated maximum secondary current is 0·5 or 1 ampere. The secondary voltage of voltage transformers is 110, with the rated pressure applied to the primary windings. The advantages of current and voltage transformers in the field of A.C. measurements are that they enable standard movements to be used for all nominal ratings, variations of the rated primary currents and voltages being taken care of by the scale or dial markings. In the field of automatic protection, current and voltage transformers have a use which is more extended than when they are used for measuring instruments, as the circumstance of their providing in insulated circuits, currents or voltages proportional to those in the main circuit enables the secondary currents or voltages to be combined, by the interconnection of the secondary windings, so that currents or voltages in several circuits, or in different parts of the same circuit, can be vectorially added or subtracted.

The proportionality between the primary and secondary magnitudes of current or voltage transformers is only approximate. For electrical measurements it is of cardinal importance that the errors of the transformers, or the departures of the actual from the nominal ratios, and the phase differences between primary and secondary magnitudes, should be as small as possible, and the problem of the reduction of these errors is assisted by the fact that accuracy is only required in a current transformer used for electrical measurement up to currents not greatly in excess of its normal rating, while in the case of instrument voltage transformers it is only the errors at the normal voltage which are of moment. The requirements in regard to accuracy are somewhat different when protective transformers are concerned. The use of voltage transformers is avoided as far as possible in the design of protective devices, but when these transformers are used, their characteristics at the low voltages which exist under fault conditions become of some moment. Protective current transformers are installed mainly for the purpose of dealing with conditions in which currents very much in excess of the normal values are flowing. While, therefore, the characteristics of instrument transformers under heavy overload or short-circuit conditions are not of any great importance, the performance of protective current transformers under such conditions is of the greatest moment. Generally speaking, it may be said of protective current transformers that great nominal accuracy of performance is not a matter of such importance as that the characteristics of the transformers associated in combination shall be practically identical both in normal and in overload and short-circuit conditions.

The Rating of Current and Voltage Transformers.—There are two distinct ratings for a current transformer: the maximum primary current, and the maximum output in volt-amperes obtainable from the secondary circuit without certain specified errors in ratio and phase being exceeded. Current transformers are dealt with in B.S.S., No. 81, 1936, for Instrument Transformers, and although this specification is framed from the point of view of electrical measurements, its principal provisions may conveniently be reviewed.

It will be well, at this stage, to explain that, although the secondary output of a current is stated in volt-amperes, this value of the output refers only to the condition when the rated primary current is flowing. The rated secondary output really implies the maximum impedance of the secondary circuit, and, this impedance being fixed, the secondary output in volt amperes will vary as the square of the secondary current. The output at one-fifth of the rated primary current will therefore be only one twenty-fifth of the rated value in volt-amperes. In the current B.S. Specification, a casual reading might induce a belief that the rated volt-ampere output must be delivered, subject to the stipulated limits of error, with currents down to one-tenth of the rated value. In view of this ambiguity it is to be wished that the output of a current transformer were expressed in terms of the impedance of the secondary circuit.

The term burden is now used to specify the characteristics of the external circuit of either a current or a voltage transformer. The application of the word is, however, somewhat vague. Its specification in volt-amperes suggests that it refers to the actual secondary output of the transformer. On the other hand, the apparatus supplied by this secondary circuit, together with the connecting leads, are generally referred to as the burden. This apparent confusion between electrical output and the circuit in which this output is absorbed does not in practice lead to any ambiguity.

Although, from the point of view of the operation of protective relays, the errors of current transformers are not of such vital importance as when electrical measurements are concerned, yet, not only is a certain standard of accuracy requisite for protective transformers in many circumstances, but the magnitude of the errors in normal conditions may give some indication of the probable performance of the transformer when the primary winding is carrying current much in excess of the rated value. The ratio error of a current transformer is the difference between the actual and the nominal ratios expressed as a percentage of the nominal ratio. The phase error is expressed as the angular separation of the vector of primary current and that of the secondary current reversed. The specification of the ratio characteristic as a percentage error requires some convention of sign to indicate whether the secondary current is above or below its nominal value. A more convenient specification of this ratio characteristic would be that of actual to nominal secondary current. Phase errors are usually expressed in minutes of angle. Actual measurements of phase error lead to the radian or circular measure of the angle between the primary and secondary current vectors, and the specification of this angle in radians is most convenient for theoretical calculations.

Instrument transformers are grouped by the British Standards Institution in several classes, according to the duty for which they are required. These classes are as follows :—

Class AL. For precision laboratory work.

Class BL. For testing work in conjunction with sub-standard instruments.

Class AM. Current transformers for precision industrial metering.

Class BM. Current transformers for industrial metering of sub-standard grade.

Class CM. Current transformers for general industrial metering.

Class A. Current and voltage transformers for use with sub-standard indicating voltmeters. Voltage transformers for precision industrial metering.

Class B. Current and voltage transformers for use with first-grade indicating and graphic instruments. Voltage transformers for metering.

Class C. For use with first-grade instruments.

Class D. For use where high accuracy is not important.

The rated burdens for current transformers are as follows :—

Classes A, B, C, and D	2½, 5 and 15 VA.
Classes AM and BM	2½, 5, 15, and 30 VA.
Class CM	1½, 5, and 15 VA.
Classes AL and BL	7·5 VA.

For voltage transformers the rated burdens are as follows :—

Class A	50, 100, and 200 VA.
Classes B and C	15, 50, and 100 VA.
Classes AL and BL	10 VA.

The limits of error for various classes of current transformers are given in the following tables :—

METERING CURRENT TRANSFORMERS.

Class	Absolute Error				Variation in Error	
	From 120% to 20% of rated current		From 20% to 10% of rated current		From 120% to 10% of rated current	
	Ratio %	Phase Mins	Ratio %	Phase Mins	Ratio %	Phase Mins
AM	1	30	1	30	0 5	15
BM	1	35	1 5	50	1	25
CM	1	90	2	120	1 5	60

OTHER CLASSES OF CURRENT TRANSFORMERS

Class	Absolute Error					
	From 120% to 60% of rated current		From 60% to 20% of rated current		From 20% to 10% of rated current	
	Ratio %	Phase Mins	Ratio %	Phase Mins	Ratio %	Phase Mins
AL	0 15	3	0 15	4	0 15	6
BL	0 5	10	0·0	15	0 5	20
A	0 5	35	0 5	35	1 0	50
B	1 0	60	1 0	60	1 5	90
C	1 0	120	1 0	120	2 0	180
D	5 0	—	5 0	—	—	—

The above values of the errors correspond to the rated burden, the power factor of this burden being unity, the external secondary circuit, in other words, being non-inductive The standard frequency is 50.

Voltage transformers, like current transformers, also have two distinct ratings, primary voltage, and secondary output. The ratio and phase errors of voltage transformers are defined in precisely the same fashion as those of current transformers. The limits of error for voltage transformers are given in the following table, in which those in the principal column 1 refer to conditions in which the applied voltage is between 90 and 100 per cent. of its rated value, and the burden between 25 and

100 per cent. of its rated value non-inductive; whilst the values in principal column 2 refer to conditions in which the voltage is between 90 and 106 per cent. of the rated value and the burden between 10 and 50 per cent. of the rated value at a power factor of 0·2.

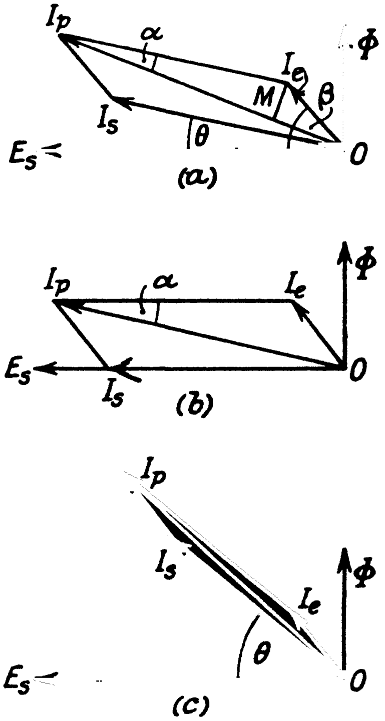
Limits of Error for Voltage Transformers.

Class.	1.		2.	
	Ratio. %.	Phase. Minutes.	Ratio. %.	Phase. Minutes.
A	0·5	20	0·5	40
B	1·0	30	1·0	70
C	2·0	30	—	—
D	5·0	—	—	—

For classes AL and BL the limits of ratio error are 0·25 and 0·5 per cent. respectively, and the limits of phase-error 10 and 20 minutes respectively at any primary voltage between 80 and 110 per cent. of the rated voltage with any burden of unity power factor not exceeding the rated burden.

The specification of a standard frequency has a different meaning for a voltage transformer from that for a current transformer. A current transformer will operate on a circuit having a frequency lower than that for which it is designed, but its errors will be greater than when it is used in a circuit of standard frequency. A voltage transformer, on the other hand, can only be used in circuits of a frequency not less than that for which the transformer is designed.

The Theory of the Current Transformer.—A current transformer essentially comprises an iron core carrying two windings, the one connected in the circuit carrying the current to be measured being designated the primary, and the other, connected to the burden consisting of the relays or instruments responsive to the main current, being designated the secondary winding. The flow of current in the primary winding produces an alternating magnetic flux in the core, and this flux induces an E.M.F. in the secondary winding, which results in the flow of a secondary current when this winding is connected to an external closed circuit. The magnetic effect of the secondary current is, in accordance with fundamental principles, in opposition to that of the primary, and the value of the secondary current automatically adjusts itself to such a value that the resultant magnetic effect of the primary and secondary current is such as to produce the flux necessary to induce the E.M.F.



Φ = Core Flux.
Is = Secondary Current.
Ip = Primary Current.
Ie = Exciting Current
Es = Secondary E.M.F.

FIG. 1.—THE ELEMENTARY VECTOR DIAGRAM OF A CURRENT TRANSFORMER.

required to drive the secondary current against the impedance of the circuit in which it flows.

The elementary vector diagram of a current transformer is shown in Fig. 1 (a), a nominal ratio of transformation of unity being assumed. The vector of secondary current I_s lags that of secondary E.M.F., E_s, by an angle θ, depending upon the power factor of the secondary circuit. To produce the E.M.F., E_s, a flux is required which is represented by a vector Φ, in phase quadrature with E_s. An exciting current, I_e, is in turn required to produce the flux, and, due to core loss, this current will lag E_s by an angle β, which is less than 90 degrees. This exciting current is derived from the primary current I_p, which is accordingly represented by a vector which is the resultant of I_s and I_e.

When a current transformer is used for the operation of measuring instrument the magnitude of I_e is relatively much less than is shown in the diagram, this magnitude being of the order of one or two per cent. of the primary current. The magnetic effects of the primary and secondary currents are then approximately equal, and as these effects depend upon the product of amperes by turns, the ratio of the primary to the secondary currents is inversely as the ratio of primary to secondary turns.

If, in the diagram Fig. I (a), a line I_eM be drawn perpendicular to I_p, then, provided the ratio of I_e to I_p is small, the ratio error is given by $\frac{OM}{I_p}$, and the phase error, α, in radians, by $\frac{I_eM}{I_p}$. As β is the angle between the vectors I_e and E, we can write the ratio error as:

$$\frac{I_e \cos(\beta-\theta)}{I_p} = \frac{I_e(\cos\beta\cos\theta+\sin\beta\sin\theta)}{I_p}$$

θ being the angle between the vectors of secondary current and voltage. Now $I_e \cos\beta$ is the component of the exciting current in phase with E, and is usually known as the core loss component, I_c, while $I_e \sin\beta$, the component in phase with Φ, is usually known as the magnetising component, I_m. The ratio error thus can be expressed as:

$$\frac{I_c\cos\theta + I_m\sin\theta}{I_p}.$$

The phase error, α, can similarly be expressed in radian measure as

$$\frac{I_e\sin(\beta-\theta)}{I_p} = \frac{I_m\cos\theta - I_c\sin\theta}{I_p}.$$

The errors of a current transformer thus depend upon the magnitude and phase of I_e, and upon the power factor of the secondary burden. The secondary E.M.F., E, is equal to the product of secondary current and secondary impedance. The flux Φ will be directly proportional to the secondary E.M.F., but there is no simple relationship between I_e and Φ. The actual relationship between these quantities cannot be expressed by means of a rational formula, but can only be determined experimentally. The nature of this relationship will be considered in detail in a subsequent section.

The dependence of the current transformer errors upon θ, the phase angle of the secondary burden, is illustrated by the vector diagrams, Figs. 1 (b) and (c). In Fig. 1 (b) we have the case when the secondary current is in phase with the secondary E.M.F. The ratio error is relatively small, and this error and the phase error are manifestly proportional, respectively, to the core loss, and the magnetising components of the exciting current, as is shown by the formulas above. In Fig. 1 (c) we have the condition when the phase angle of the secondary current is approximately equal to that of the exciting current, and in this condition the phase error tends to disappear. As a general rule, the angle θ is less than β, so that the secondary current vector leads that of the primary current. In the unusual case of θ being greater than β, the phase error would be reversed with respect to the normal conditions and I_s would lag on I_p.

When the conditions under which a current transformer operates are such that I_e is no longer small in relation to I_p, the formulas given above will not be applicable.

The Equivalent Circuit for a Current Transformer. - It appears from the above discussion that the errors of a current transformer may be considered as due to the fact that the whole of the primary current is not transformed, a component being used to excite the core. Alternatively we may consider that the whole of the primary current is transformed without loss, but that the secondary circuit is shunted by a parallel circuit the impedance of which is such that the equivalent of the exciting current flows in it. The circuit shown in Fig. 2

is the equivalent of the actual circuit which comprises a transformer with a turns ratio of unity. In this circuit the current transformer secondary is connected in shunt to two impedances in series representing respectively the impedance of the external burden and that of the secondary windings. The voltage drop across these impedances will evidently be equal to the E.M.F. of the transformer when delivering an equivalent current, and the current shunted by the transformer winding is equal to the exciting current I_e, necessary to produce this E.M.F. Thus the currents indicated as I_p and I_s in the diagram have the same ratio and phase relation as the primary and secondary currents when the transformer is operating in the normal way. The diagram is applicable to a transformer of any ratio, provided that the components I_p and I_s be considered to represent ampere-turns, instead of actual currents.

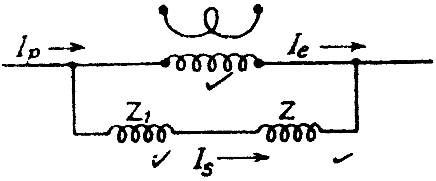


FIG. 2 – THE EQUIVALENT CIRCUIT FOR A CURRENT TRANSFORMER

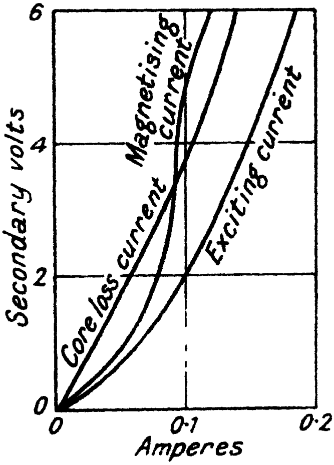


FIG. 3 —SATURATION CURVES FOR SILICON IRON

The Saturation Curve of a Current Transformer.—The equivalent circuit of a current transformer, shown in Fig. 2, suggests that the errors of transformation, which, as we have seen, depend upon the relation between the exciting current I_e and the core flux, can, as the flux is directly proportional to the secondary voltage, be studied from a consideration of the saturation curve of the transformer. This saturation curve is a graphical representation of the relation between the current and voltage in one of the windings, the secondary for convenience, the other winding being open-circuited.

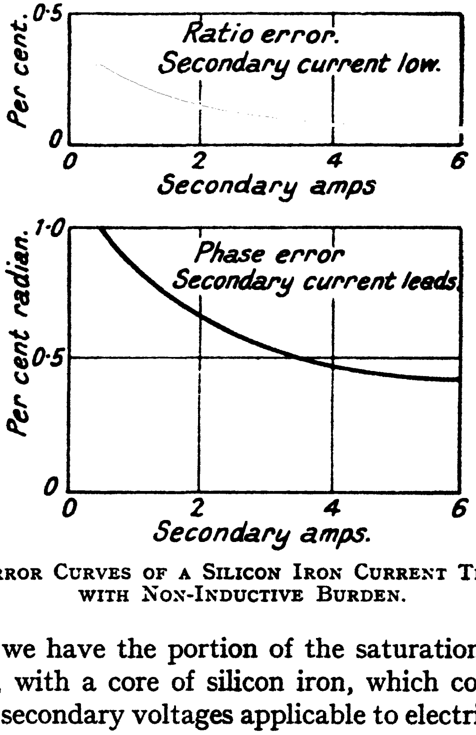


Fig. 4.—Error Curves of a Silicon Iron Current Transformer with Non-Inductive Burden.

In Fig. 3 we have the portion of the saturation curve for a transformer, with a core of silicon iron, which corresponds to the range of secondary voltages applicable to electrical measurements. The magnetising and core loss components of the exciting currents are also shown. For the low values of the secondary voltage given in this diagram, the magnetising current is seen to be approximately proportional to the square root of the secondary E.M.F. If the iron loss of the transformer in watts were proportional to the square of the secondary voltage, then I_c would be directly proportional to I_s, and the ratio error, for a secondary power factor of unity, would be constant. The eddy current loss in the core varies as the square of the flux density or as V^2, but the hysteresis loss varies as a lower power which is of the order of 1·7. The total core loss component is, therefore, like the magnetising component, relatively greater at low values of the secondary current than at its rated maximum value. Typical error curves of a current transformer with a silicon iron core are shown in Fig. 4.

The use of a nickel iron alloy, such as Mumetal, for the core, enables a great reduction in the errors to be effected by reason of the very high permeability of this material at low values of the magnetising force. A typical saturation curve of a Mumetal current transformer is shown in Fig. 5, the curve for a silicon iron transformer being also represented for the purpose of comparison. It will be seen that for a given value of the secondary voltage the exciting current for a Mumetal transformer is of the order of one-tenth of that of a silicon iron transformer. The respective errors of the transformers within the range of secondary currents represented in the diagram will, of course, be in a corresponding ratio, for identical secondary impedances.

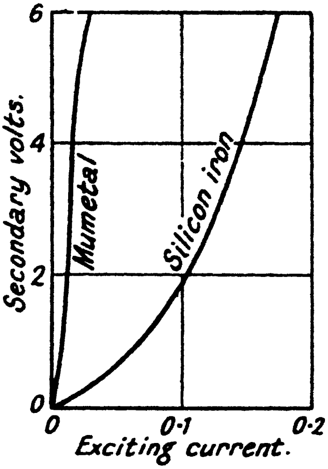


Fig. 5.—Comparative Saturation Curves for Silicon Iron and Mumetal.

The curves considered above refer to values of the secondary voltage, which correspond to primary currents not greatly in excess of the rated value. If the value of the secondary voltage is increased considerably, as will be the case with excessive primary currents, the saturation curve of the transformer takes the form shown in Fig. 6. Here are plotted the total exciting current, and the core loss component. A study of these curves shows that of the total exciting current inflects at a point corresponding to values of the secondary voltage considerably greater than that corresponding to the rated primary current, and that, in conditions of heavy overload, the exciting current increases relatively faster than the secondary voltage The curvature of the core loss current curve does not change greatly, and as the flux density in the core increases, the ratio of core loss to total current decreases. In heavy overload conditions, therefore, the angle β in Fig. 1 approaches 90 degrees.

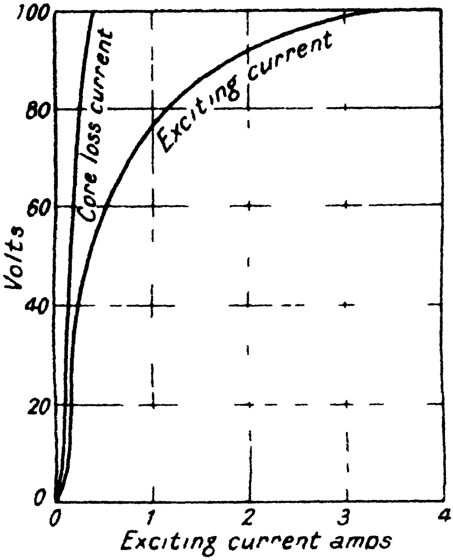


Fig. 6—Saturation Curve for a Silicon Iron Current Transformer

The saturation curve for other than small secondary voltages approximates to a parabolic form, and the exciting current is roughly proportional to the square of the voltage. As exciting current and secondary voltage are proportional respectively to the magnetising force H and the flux density B, this approximate relation is equivalent to the statement that $H \propto B^2$. Further

$$H \propto \frac{I_e N}{l}$$

and

$$B \propto \frac{V}{afN}$$

where N is the number of turns and V the voltage in the circuit to which I_e is referred, f the frequency, a the core area, and l its effective length Then, as $H \propto B^2$

$$\frac{I_e N}{l} = K \frac{V^2}{a^2 f^2 N^2}$$

and

$$I_e = K \cdot \frac{l}{a^2 f^2 N^3} \cdot V^2$$

where K is a constant independent of the dimensions of the transformer. As the errors of a transformer depend primarily on the value of I_e corresponding to a given value of V, this last expression gives the approximate relation between the errors and the constants of the transformer and the frequency. The effect of a reduction in the number of turns on each winding is seen to be very serious from the point of view of accuracy of transformation.

The Impedance of Current Transformer Windings.—The term "impedance," applied to the windings of a current transformer, may have one of several meanings. The first of these meanings to be considered is the portion of the total secondary burden contributed by the secondary winding. The secondary impedance, considered as part of the total burden, is the resultant of the resistance and the leakage reactance, this reactance being the result of the flux set up by the secondary current which is not linked with the primary winding. The value of the secondary leakage reactance depends upon the manner in which the two windings are disposed on the core. When the primary conductor consists of a straight bar in the centre of the core aperture, and the secondary winding is disposed uniformly round a circular core, the secondary leakage reactance is negligibly small. When primary and secondary windings are disposed on opposite sides of a rectangular core, the secondary reactance at normal values of the primary current may be of the same order as the resistance. With this type of construction the value of the reactance is not constant, but increases rapidly with heavy overloads, so that the lag of the current on the secondary E.M.F. tends to 90 degrees.

The impedance of the secondary circuit of a current transformer is a minimum burden, which cannot in simple circuits be eliminated. If, therefore, the impedance of the external burden is small, the performance of the current transformer will be determined by the characteristics of the secondary winding. It is only with external burdens of high impedance that the effect of the internal burden is negligible. It appears also that, unless the secondary leakage reactance is negligible, the power factor of the secondary current cannot be unity.

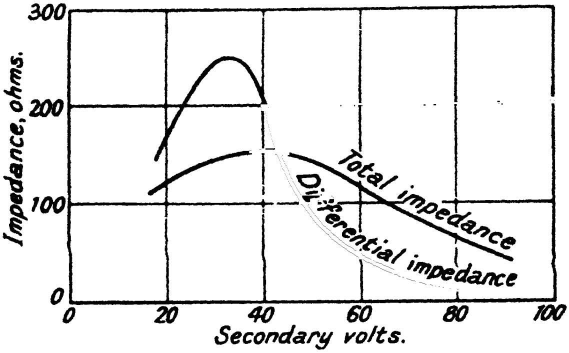


FIG. 7.—IMPEDANCE CURVES FOR A SILICON IRON CURRENT TRANSFORMER.

Referring to the equivalent circuit of a current transformer given in Fig .2, we see that the total secondary impedance is virtually shunted by an impedance which is equal to the quotient of secondary voltage by exciting current. The variation of the total open circuit impedance of the transformer secondary windings shows in a graphical manner the performance of the transformer which is to be expected in abnormal conditions. The open circuit impedance of the transformer whose saturation curve is shown in Fig. 6 has been calculated and plotted to give the curve shown in Fig. 7. The point of maximum total impedance evidently corresponds to maximum permeability of the iron of the core of the transformer.

In certain circumstances it is of interest to know for various values of the primary current, the increase in this current required to give a fixed increase in the secondary current. This will depend upon the increase in the exciting current for a given fixed increase in the secondary voltage, or to dV/dI_e. This ratio may be called the differential impedance, and its values for the transformer already considered are shown in Fig. 7. The maximum differential impedance is greater than the maximum total impedance, and it occurs at a point on the saturation curve where the curvature changes sign.

Construction of Current Transformers.—We have already seen that the number of turns on a current transformer has an important bearing upon its accuracy in overload conditions. If the secondary voltage is increased to such an extent that the exciting current is more than a small fraction of the primary current, referred to the same winding, the errors of the transformer cease to be such as can be considered small, and the ratio is said to break down. Inordinate increase in the exciting current occurs when the flux density in the iron of the core approaches saturation. The ratio between the secondary voltage at saturation and that at the rated primary current is the number of times full load current the transformer will handle before a serious breakdown of ratio takes place. The larger the number of turns the greater will be the secondary voltage at the saturating value of the flux density.

Although, theoretically, it is possible to retain the accuracy of a current transformer on heavy overloads by the provision of a large number of turns, there are serious objections to this procedure when the transformer primary is liable to be called upon to carry excessive short-circuit currents owing to the large mechanical stresses set up by these currents and to their heating effects. The mechanical stresses set up by short-circuit currents tend to repel conductors carrying currents in opposite directions and also to force the windings into a circular form.

A current transformer in an extra high-pressure circuit with a considerable number of primary turns might be wrecked on the occurrence of a short-circuit, by the bursting of the primary winding. Further, the greater the number of turns, the greater will be the total heating effect of the short-circuit current. Due to the dangers attending the use of primary windings, with even a limited number of turns, on extra high-pressure circuits, the use of current transformers having a primary conductor consisting of a straight bar, is sought after by switchgear designers in the interests of safety. A straight primary conductor gives the equivalent of one turn, and the nominal number of secondary turns is then equal to the nominal ratio of primary to secondary currents. Transformers with a single straight primary conductor are known as bar primary current transformers in contradistinction to those having more than one primary turn, which are known as wound primary current transformers. Current transformers are often constructed without a primary conductor, so that they can be fixed over the insulator bushing of an oil circuit-breaker. Such transformers are usually known as bushing current transformers.

We have seen, above, the bearing of the number of secondary turns on the performance of a current transformer. It is usual to express this characteristic as the product of rated primary current by primary turns.

Satisfactory accuracy for measuring purposes cannot be obtained with transformers having silicon iron cores, unless the number of primary ampere turns is at least 600, this corresponding to a nominal 120 turns on a 5A secondary winding. As the number of secondary turns is reduced below the value, the total flux required to produce the secondary voltage increases in the inverse ratio, and this increase in flux can only be obtained by increasing the density, if the core area remains constant. To increase the density, not only is a greater value of the magnetising force required, but as this must be produced by a smaller number of turns, the exciting current is still further increased. Rapid falling off in accuracy thus takes place as the ampere turns are reduced below 600. For current transformers designed for the accurate measurement of energy, 1,000 ampere turns are considered good practice, if silicon iron is used for the core.

We have already referred to the use of a nickel iron alloy, such as Mumetal, for the cores of current transformers. The superior magnetic properties of this material enable either extreme accuracy to be obtained with a comparable design to that used for a silicon iron transformer, or, alternatively, satisfactory accuracy to be secured with a number of ampere-turns very much less than that requisite for a transformer of the older type. The magnetising force produced by the exciting current is proportional to I_eN/l, and if μ is the permeability of the material of the core the flux density will be

$$\mu . \frac{I_eN}{l}$$

this density is also proportional to $\frac{V}{afN}$.

With given core dimensions, frequency, and secondary voltage, the numbers of turns required for a stipulated exciting current will be in the inverse ratio of the square roots of the permeabilities of the magnetic materials used. The permeability of Mumetal for densities below saturation is from 10 to 40 times that of silicon iron, so that for a given secondary burden a core dimension equivalent accuracy can be obtained with Mumetal for a number of turns from ⅓ to ⅙ that required when silicon iron is used. The use of Mumetal is at the present time somewhat restricted by its high cost, and, accordingly, it is customary when possible to obtain economy in the use of the material by using a value of the flux density at the ratio current which is about twice that customary for silicon iron transformers. The increase in the density enables the total flux, fixed by the secondary voltage, to be obtained with a correspondingly reduced core area.

The point at which the ratio of a current transformer commences to diverge from the nominal ratio by more than a trifling amount depends upon the ratio of the flux density at the rated primary current and burden to the saturation value of the density. The saturation values of the flux density for Mumetal and silicon iron are respectively about 9,000 and 16,000. This circumstance, together with that of the frequent use of a higher normal density with Mumetal than with silicon iron, renders the Mumetal transformers less able to maintain their ratio at heavy overloads than silicon iron transformers of comparable accuracy. When stability of ratio is required over a very large range of primary currents, silicon iron transformers are frequently most suitable.

The comparative saturation curves for silicon iron and Mumetal for densities approaching saturation are shown in Fig. 8. Typical performance curves for silicon iron transformers under overload conditions are shown in Fig 9.

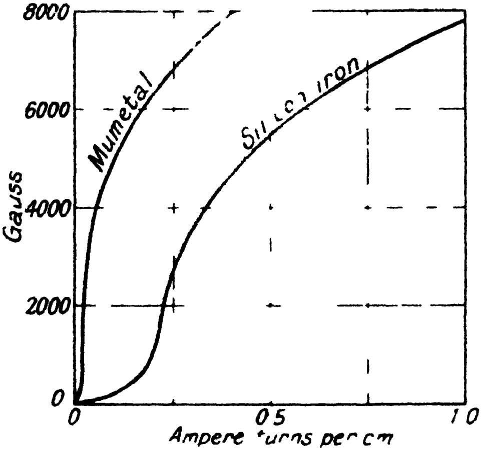
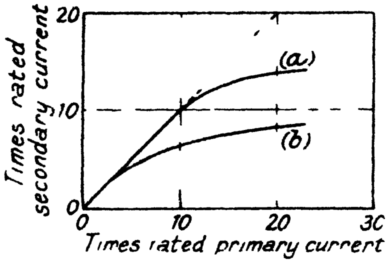


Fig 8.—Alternating B H Curves for Silicon Iron and Mumetal



a 000 amp turns 30 VA
b 200 " 5 VA

Fig 9.—Overload Performance of Current Transformers

We have already alluded to the fact that 0·5A and 1A are standard values for the rated secondary current of a current transformer. The advantages of this value as compared with the older value of 5A requires a few words of explanation The total secondary burden of a current transformer includes not only the internal impedance of the secondary winding and the impedance of the instruments and relays which it supplies but also that of the connecting leads. In modern outdoor switchgear equipments, the distance between the current transformers and the relay panels may be very considerable, and with a rated secondary current of 5A, the impedance of these leads constitutes a considerable burden. If the rated secondary current is only 0·5A, the burden imposed by leads of standard section will be reduced to one-hundredth of the value corresponding to a 5A secondary current. Modern progress in the design of instruments and relays has been in the direction of the reduction in the volt-ampere burden imposed upon the current transformers, and this improvement, together with the reduction in effective burden imposed by the leads obtained by the use of the smaller secondary current, greatly extends the sphere of application of bar primary transformers with a small number of ampere-turns.

There is a further advantage in the use of 1A or 0·5A as the rated secondary current to which allusion must be made. It is usual to obtain a partial correction for the ratio error of a current transformer due to the exciting current, by winding the secondary with one or more turns less than the number corresponding to the nominal ratio. This procedure increases the ratio of secondary to primary current, and gives a partial correction for ratio error by an amount which is constant for all loads. This adjustment of the number of secondary turns is known as turns compensation, and, as the compensation can, as a rule, only be made by the omission of integral numbers of turns, the sensitivity of the compensation diminishes as the number of secondary turns diminishes. With 120 secondary turns, for instance, the smallest turns correction for ratio error is 1/120 or 0·8 per cent. With bar primary or bushing transformers for low rated primary currents, the omission of even one turn gives altogether too coarse a correction. A 100/5 transformer, for instance, with 20 secondary turns, could not have a smaller turns correction than 5 per cent. This difficulty is completely overcome when 0·5A is adopted as the value of the rated secondary current, as, the number of secondary turns being increased tenfold, the turns compensation can be applied in sufficiently fine steps even with bar primary transformer having so low a number of ampere turns as 50.

The Performance of a Current Transformer with a Burden of Constant VA.—An excellent illustration of the characteristics of a current transformer is illustrated by an investigation of the value of the primary current required to produce a given value of the secondary current in a circuit, the volt-ampere consumption of which is the same for all values of the secondary current. Such an investigation would be called for, in practice, if it were required to determine the correct setting of a relay, to give operation with the minimum primary current, the volt-amperes in the relay being assumed to be independent of the setting value. If the relay setting is reduced to a very low value, the impedance of the relay will, for constant volt-amperes, increase inordinately, and, due to the high secondary voltage required to give the required secondary current, the ratio may be so adversely affected that the primary current may actually be greater than when a higher value of the setting and a correspondingly lower impedance is employed. This point can conveniently be investigated approximately by assuming a parabolic saturation curve for the current transformer. Let it be assumed also that the secondary current is in phase with the secondary E.M.F., and that the exciting current is in phase with the flux. Then I and I_s will be in quadrature, and, if the turns ratio be assumed to be unity,

$$I_p^2 = I_s^2 + I_e^2$$

then, assuming $I_e = KV^2 = KI_s^2Z^2$,

where Z is the value of the impedance of the secondary circuit

$$I_p^2 = I_s^2 + K^2I_s^4Z^4.$$

If M is the value of the constant VA of the burden, then

$$Z = \frac{M}{I^2}$$

and $$I_p^2 = I_s^2 + \frac{K^2M^4}{I_s^4}.$$

From this equation connecting I_p and I_s we see that, when I' is very small, the term $\frac{K^2M^4}{I_s^4}$ is the only one of importance, and I_p^2 is proportional to $\frac{1}{I_s^2}$. When I_s is very large, the second term of the equation can be neglected and $I_p = I_s$. The form of the graph of the function connecting I_p and I_s is therefore as shown in Fig. 10.

We can find the minimum value of I_p by differentiation. Thus:

$$\frac{d(I_p^2)}{dI_s} = 2I_s - \frac{4K^2M^4}{I_s^5} = 0$$

Whence $\qquad I_s^6 = 2K^2M^4$ and $I_s = 2^{\frac{1}{6}}K^{\frac{1}{3}}M$.

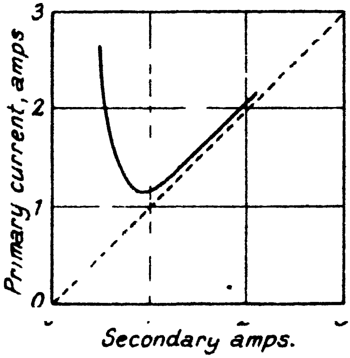


FIG. 10.—CHARACTERISTIC OF CURRENT TRANSFORMER WITH CONSTANT SECONDARY VA OUTPUT

Substituting this value of I_s in the original equation we find

$$I_p = 3^{\frac{1}{2}}.2^{-\frac{1}{3}}.K^{\frac{1}{3}}M^{\frac{2}{3}}$$

and
$$\frac{I_p^2}{I_s^2} = \frac{3}{2}.$$

We have already seen that the factor K in the above calculation is equal to

$$\frac{K_1}{a^2f^2N^3}$$

where K_1 is independent of the dimensions of the transformer.

We therefore have, for the minimum value of the primary current which will operate a relay requiring M volt-amperes:

$$I_p = K_1 . M . \frac{1}{a f N}.$$

The results of this investigation are merely approximate, because the assumed relation between I_e and the secondary voltage is not strictly true. Although the equations for the values of the minimum currents are based upon approximate assumption, and are not borne out exactly by experimental tests, they do represent, in a general way, the relation between these currents and the constants of the transformer and of its burden.

We can illustrate the results obtained above by a numerical example by considering a current transformer with which one ampere exciting current gives a secondary E.M.F. of 20 volts. The equation connecting I_e and V will then, on the assumption of a parabolic saturation curve, be

$$I_e = \frac{V^2}{400}.$$

Suppose we desire to use this transformer to energise a relay of such a type that, whatever may be the operating current, the volt-ampere consumption at this current is 15. The substituting in the equation $I_s^6 = 2K^2M^2$ we have

$$I_s^6 = 2 \cdot \frac{1}{400^2} \times 15^4,$$

neglecting the impedance of the transformer windings,

whence $I_s = 0{\cdot}9\text{A approx.},$

and $I_t = \sqrt{\left(\frac{3}{2}\right)}\, I_s = 1{\cdot}11\text{A}$

for a turns ratio of unity.

These results indicate that the minimum primary current which will operate the relay is 1·11A, and this operation is obtained when the relay setting is 0·9A. If a relay, absorbing 15VA, and arranged to operate at a lower current, is used, then; in spite of its increased sensitivity, the increased impedance of the secondary circuit of the transformer will result in a greater current than 1·11A in the primary winding being required for its operation.

The Secondary Output of a Current Transformer with Constant Primary Current.—We have already seen that if the impedance of the secondary circuit of a current transformer is constant, the ratio may remain sensibly constant for values of the primary current considerably in excess of the rated value. If, however, the primary current is maintained constant, an increase in the secondary impedance will always result in a decrease of the secondary current, due to the increase in the exciting current required to furnish the higher secondary voltage. The manner in which the secondary current varies as, with a constant primary current, the secondary impedance is varied, is shown in Fig. 11. From this it will be seen that, starting with a short-circuited secondary winding and gradually increasing the external impedance, the secondary current steadily decreases, at first slowly, then more rapidly, and finally at an increasingly lower rate as the curve becomes asymptotic to the zero axis of current.

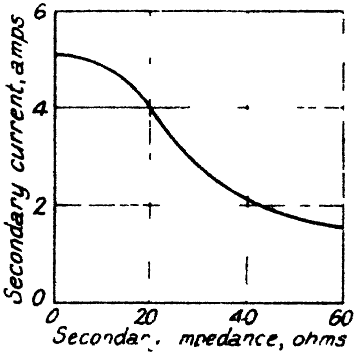


Fig. 11.—Performance of Current Transformer with Varying Secondary Impedance

The secondary output of the transformer, in volt-amperes, is zero with short-circuited secondary, and zero with infinite secondary impedance when the current is zero. Between these extreme values of the impedance there is one which gives a maximum value for the volt-amperes, and as the ability of a current transformer to operate a relay with a given primary current depends upon its volt-ampere output, the maximum value of this output is a matter of importance, particularly with transformers having a limited number of ampere turns.

We can investigate this matter analytically by assuming, as we have done in the last section, that the saturation curve of the current transformer is a parabola, and that the secondary and exciting currents are in phase quadrature. We then have

$$I_p^2 = I_s^2 + I_e^2 = I_s^2 + K^2 I_s^4 Z^4$$

As we wish to investigate the relation of the volt-amperes M with the impedance we eliminate I_s, thus,

$$I_p^2 Z = M + K^2 M^2 Z^3.$$

Solving this equation for M we find

$$M = \frac{\sqrt{(1 + 4K^2 Z^4 I_p^2)} - 1}{2K^2 Z^3}.$$

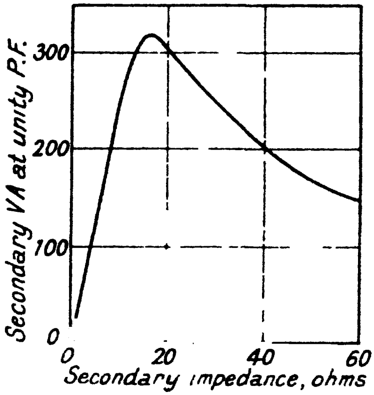


Fig 12.—Secondary Output of Current Transformer with Varying Secondary Impedance

When Z is small we can use the approximate value, $1 + 2K^2Z^4I_p^2$ for the square root and M is then proportional to I_p. When Z is very large, the square root is sensibly equal to $2KZ^2I_p$ and M is then proportional to $1/I_p$. The form of the curve representing the relation between M and Z is shown in Fig. 12.

If we differentiate the expression for M with respect to Z and equate the derived function to zero, we find that the minimum value of M is given when

$$Z^2 = \frac{\sqrt{3}}{2} \cdot \frac{1}{I_p K}$$

and the actual minimum value of M is

$$\frac{2^{\frac{1}{2}}}{3^{\frac{3}{4}}} \cdot \frac{I}{K^{\frac{1}{2}}}$$

by substituting in the original equation the value of Z, giving the maximum volt-amperes, we find that, with this maximum output,

$$I_s = \frac{2}{3} I_p.$$

The factor K in the above calculation is equal to

$$K_1 \frac{1}{a^2 f^2 N^3}$$

K_1 being a constant independent of the dimensions of the transformer.

The maximum value of the volt-amperes is thus

$$\frac{2^{\frac{1}{2}}}{3^{\frac{3}{4}}} \cdot \frac{I}{K^{\frac{1}{2}}} = K_2 \, . \, (IN)^{\frac{3}{2}} \, . \, \frac{a.f.}{l^{\frac{1}{2}}}.$$

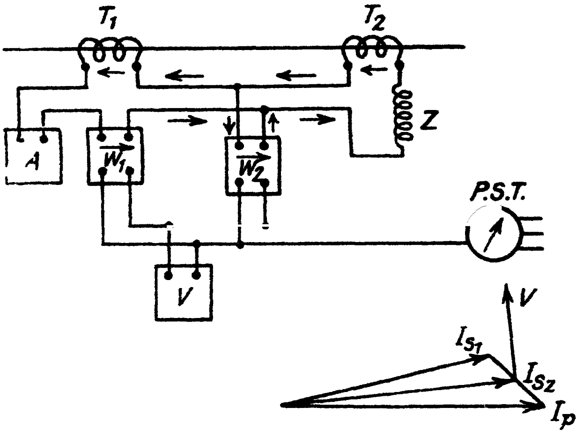
The result of this calculation shows that, on the assumptions that have been made the maximum volt-ampere output a current transformer can give for a given primary current is proportional to the 3/2 power of the primary ampere turns, and directly proportional to the frequency. Owing to the fact that the basic assumptions are only approximately true, the results obtained can merely be taken as giving a general indication of the bearing of the dimensions and number of turns of a transformer upon the output which can be obtained for a given primary current, but the proportionality between this maximum output and the 3/2 power of the ampere turns is often very closely borne out by experiments.

Double Current Transformations.—It will be clear from what has gone before that the errors of a current transformer are due to the impedance of the secondary circuit, that of the primary circuit having no effect on these errors, since the voltage required to drive the primary current through the primary winding is derived directly from the external circuit. Occasionally, in protective gear circuits, the secondary current of one current transformer is passed into the primary winding *of a second transformer. In such a case the secondary voltage* of the main transformer must be sufficient to overcome the total equivalent impedance of both circuits of the second transformer. If the cross-sections of the two windings of the second transformer are in the ratio of the currents they carry, the total equivalent impedance of this transformer will be approximately equal to double that of the primary winding, but the total effective burden in the secondary circuit of the main transformer will include that of the external burden of the second transformer in addition to that due to the windings of this transformer. These components of the effective burden of a current transformer, when supplying the primary winding of a second transformer, must be carefully borne in mind. The total error of transformation in the tertiary circuit will be the sum of the errors of both of the transformers.

The burden imposed on one current transformer, by another transformer supplying a tertiary circuit, can be measured very easily by passing the rated secondary current through the primary winding of this transformer while its secondary winding is connected to the apparatus it supplies, and measuring the voltage drop across the primary terminals. The voltage drop per primary ampere will be the effective impedance in the secondary circuit of the main transformer

The Measurement of Current Transformer Errors.--When a current transformer is used for the measurement of current or power it is of importance that its errors be known with considerable accuracy at normal values of the primary current. For the operation of protective relays, high inherent accuracy is not, as a general rule, requisite. It is, however, often of considerable importance that the errors of protective current transformers be known for high values of the primary current. We proceed to describe methods of testing current transformers, first with normal values of the primary current and secondly on heavy overloads. These methods are capable of giving commercial accuracy, and are of sufficient precision when the performance of the transformers in the operation of protective relays is concerned.

At normal values of the primary current, a current transformer can conveniently be tested by methods whereby its secondary current is compared with the secondary current of a standard transformer, having known errors, and whose primary winding carries the same current as that of the transformer under test. A diagram of connections for a test of this kind is shown in Fig. 13. T_1 is the standard transformer, whose errors when supplying the ammeter A and the wattmeter W are presumed to be known for all values of the primary current. The primary of T_1 is connected in series with that of the test transformer T_2, to a circuit from which a current equal to that of the rated primary current of T_1 and T_2 can be obtained. The secondary of T_2, connected to its actual burden Z, is connected in series with the secondary of T_1. A wattmeter W_2 is connected to the secondary circuit in the manner shown. The voltage circuits of the two voltmeters are, together with a voltmeter V, connected in parallel and supplied from the secondary winding of a phase-shifting transformer. If the impedance of the current coil of W_2 be negligible, then it will readily be understood that the current in this coil is the difference between the secondary currents of the two current transformers. It is also evident, from the vector diagram, that the component of the current in W_2 which is in phase with the main



I_p = Primary Current
I_{s_1} = Secondary Current of Standard Transformer
I_{s_2} „ „ „ Test „
V Phase-Shifter Voltage

FIG. 13 DETERMINING THE ERRORS OF A CURRENT TRANSFORMER

secondary current I, expressed as a fraction of I, is equal to the difference of the ratio errors of the two transformers. Similarly the component of the current in W_2, in phase quadrature with I_1 expressed as a fraction of I, will be the radian measure of the difference in the phase errors of the transformer. The quadrature component of the current in W_2 is determined by setting the rotor of the phase shifter so that W_1 reads zero, and observing the reading of W_2. With a zero reading of W_1, the voltage exciting W_2 is in quadrature with I, and the reading of W_2 divided by that of V, gives the quadrature component of the difference current. By rotating the phase shifter secondary through 90 degrees, the voltage exciting W_1 is brought into phase with I_1 and the reading of W_2 divided by that of V will give the in-phase component of the difference current, from *which the difference in the ratio errors can be calculated.*

In addition to a knowledge of the differences in the errors of the two transformers, we require to know the sense of these errors, that is, whether those of T_2 are smaller or greater than those of T_1. This can readily be determined. The sense of the difference in the ratio errors is immediately indicated by the direction of the reading of W_2. A study of Fig. 13 will show that as like terminals of the voltage circuit are connected to the same terminal of the phase-shifting transformer, the relative directions of the currents in W_1 and W_2 are as shown by the arrows. If the wattmeters read in the same direction, the current given by T_2 is manifestly greater than that given by T_1, since part of the current from T_2 is seen to pass into W_2.

The sense of the difference in phase error can be determined by slightly displacing the phase of the voltage exciting W_2 from the quadrature position, and observing the alteration in the reading of the wattmeter. A study of the vector diagram in Fig. 13 shows that if the phase of the exciting voltage is advanced, the reading of W_2 will increase, this indicating that the secondary current of T_1 leads that of T_2. If the secondary *current of T_2 had been greater than that of T_1, then a lead of* the current from T_2 over that from T_1 would have been indicated by a reduction in the reading of W_2 with the exciting voltage slightly advanced in phase in respect to the quadrature position. We have already referred to the fact that the current in W_2 is equal to the difference between the secondary currents of T_1 and T_2 only if the impedance of W_2 is negligible. The effect of the impedance of the current coil of W_2 is evidently to cause the current in it to be less than the actual difference current. The magnitude of this kind of effect will be referred to in greater detail in the next chapter, but, at this stage, we may say that, with current transformers rated for 15 VA, the wattmeter W_2, if of the normal portable sub-standard variety, should not be rated for less than 1 A. Larger readings can be obtained by lower current ranges, but the accuracy of the test will suffer due to the effect of the wattmeter impedance in reducing the current in the difference circuit.

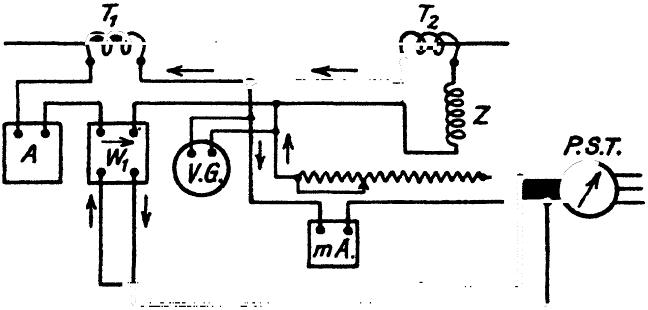


Fig. 14.—An Alternative Method of Determining the Errors of a Current Transformer.

An alternative method of testing current transformers at normal currents is illustrated in the diagram of connections, Fig. 14. The circuit is generally similar to that shown in Fig. 13, but, instead of a wattmeter to measure the difference current, the subsidiary circuit connected to the main secondary circuit is taken, through an adjustable resistance and a milliammeter, to the rotor of a phase-shifting transformer. A vibration galvanometer, VG, is connected to the points of the main secondary circuit, to which the leads from the phase shifting transformer are joined. The procedure is first to set the phase shifter voltage so that W_1 reads zero. This voltage is then in quadrature with I, and the pointer of the phase shifter is set to 90°. The magnitude and phase of the current from the phase shifter are now so adjusted that the vibration galvanometer gives a null indication. When this condition obtains the current in the milliammeter is equal to and in phase with the difference current of the two transformers, and the in-phase and quadrature components of this current can be immediately calculated since the reading of the phase-shifting transformer gives the angle of phase difference between the difference current and the main secondary current. If this angle be θ and I_1 the current in mA, and I the main secondary current as indicated by A, the difference in ratio error will be $\frac{I_1}{I}\cos\theta$, and the difference in phase error, $\frac{I_1}{I}\sin\theta$. The sense of the phase errors is determined exactly as outlined in the previous test, recollecting that the voltage exciting W_1 is in phase with the current in the milliammeter. The direction of the reading of W_1 thus gives the relative direction of I_1 with respect to I.

We observe that, with this method of testing, there is no voltage between the points in the main secondary circuit to which the phase-shifting transformer is connected, when the readings are taken, as, in this condition, the vibration galvanometer is giving a null reading. The condition, with regard to the current transformers, is therefore the same as if these points were joined together. The current in the milliammeter is thus sensibly equal to the difference between the secondary currents of T_1 and T_2, and the results obtained by this test are the same as those which would be obtained by the method previously described using a wattmeter of zero impedance to measure the difference current. We may observe that the actual difference between the two secondary currents contains harmonics which are not detected either by a wattmeter or a vibration galvanometer. This circumstance is, however, common to all indirect methods of current transformer testing.

The comparison methods described above are not, as a rule, very suitable for the investigation of the performance of a transformer on heavy overloads, unless the errors of the standard transformer are known over the entire range of currents proposed to be used for the test. Further, there will often be a difficulty, excepting in well-equipped test houses, in obtaining values of the primary current of the order of ten times the rated value, excepting when this rated value is quite low.

When it is possible to obtain the requisite maximum value of the primary current for the test, the ratio characteristics of a current transformer can be obtained with sufficient accuracy, from the point of view of operation of protective gear, by a direct observation of primary and secondary currents. When this method of testing is employed, the rating of the current transformer used for the direct measurement of the primary current should be sufficiently greater than that of the transformer under test to ensure that, at the maximum value of the test current, the ratio of the measuring current transformer will be negligibly small. The secondary current of the transformer under test should be measured by means of a direct reading ammeter. As the maximum reading of this ammeter will be considerably greater than the rated secondary current of the transformer, the impedance of this ammeter will affect the burden of the test transformer to a degree which may be considered negligible.

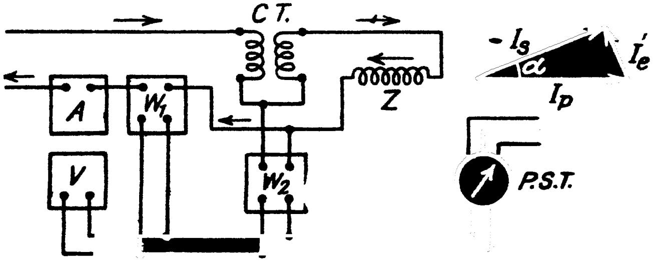


Fig. 15.—Determining the Errors of a 5/5 Current Transformer.

When bushing type transformers, without primary conductors, are to be tested in overload conditions, the test can be carried out with considerable accuracy and convenience by winding the transformer with a temporary primary winding having a number of turns equal to the nominal number of turns on the secondary. The ratio of the transformer is then unity and the primary and secondary currents can then be directly compared by using the circuit shown in Fig. 15, using a wattmeter to measure the two components of the difference current. The method in which a vibration galvanometer is used is not advisable for heavy overloads, as the harmonics in the difference current, which the vibration galvanometer is not competent to detect, may be sufficiently great to vitiate the readings of this instrument. When the ratio of the transformer begins to break down the current in the wattmeter W_2 will increase rapidly as the primary current is increased, and care must be taken that the range of the wattmeter is sufficient to deal with the difference current. The current coils of portable wattmeters will, as a rule, carry double the rated current for short periods, and this overload capacity can be utilised, the exciting voltage of W_2 being reduced if necessary.

When the breakdown of ratio occurs, the in-phase component of the difference current can no longer be taken as a measure of the ratio error of the transformer, as in these circumstances the phase error will be considerable. The vector diagram for the primary and secondary current will be as shown in Fig. 15. From this it will be seen that if I_1 and I_2 are respectively the components of I_e in phase with, and in quadrature with I_p, the magnitude of the secondary current is $\sqrt{\{I_2^2 + (I_p - I_1)^2\}}$. The phase error, α, is evidently arc sin I_2/I_s.

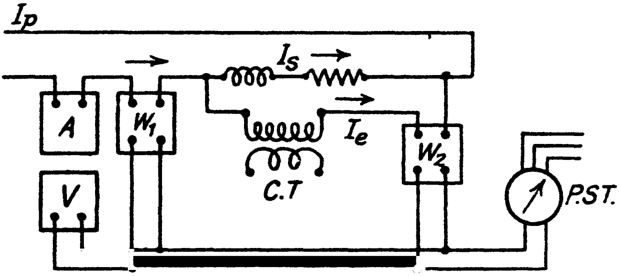


FIG. 16.—AN APPROXIMATE METHOD OF DETERMINING THE ERRORS OF A CURRENT TRANSFORMER ON OVERLOADS.

We have shown in Fig. 2 the equivalent circuit for a current transformer, based upon the conception that the exciting current may be considered as being shunted from the main secondary circuit by an impedance equal to the open circuit of the secondary winding. This equivalent circuit is the basis of a further useful approximate method of investigating the performance of a current transformer in overload conditions. The circuit is arranged as shown in Fig. 16, from which it will be seen that the in-phase and quadrature components of the exciting current with respect to the total current passing into the circuit are measured in the manner previously described by means of the wattmeter W_2. The impedance in parallel with the transformer winding must be equal to the total impedance of the secondary circuit. For a current transformer with a bar primary, having a secondary winding uniformly distributed on a circular core, the leakage reactance of the secondary winding is negligible, and the impedance in parallel with the secondary winding will consist of the normal burden of the transformer plus a resistance whose value is equal to that of the secondary winding. The method is not suitable for transformers with non-distributed secondary windings, as with this type the secondary leakage, as we have seen, not only is appreciable, but may reach a very high value at high values of the primary current. With such a transformer it is not possible to arrange that the impedance in parallel with the secondary winding in the circuit represented in Fig. 16 will, in all conditions, be exactly equal to the total secondary impedance in all conditions.

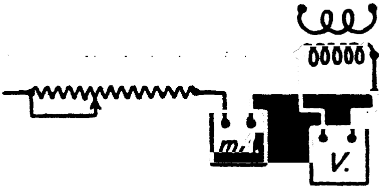


FIG 17.—DETERMINING THE SATURATION CURVE OF A CURRENT TRANSFORMER

When interpreting the results of the test just outlined the secondary current will be the vector difference of the current I_e in the transformer winding, and the main current I_p. The primary current corresponding to an observed value of I_p will be equal to I_p multiplied by the turns ratio of the transformer, and not by the nominal ratio. This is the case because the equivalent circuit shown in Fig. 2, upon which the method depends, ignores the turns compensation.

The performance of a current transformer can readily be checked at any time if the data for the saturation curve is determined at the time the transformer is put into service. The saturation curve is determined by the method illustrated in Fig. 17. The exciting current is measured by the milliammeter mA and the secondary voltage by a voltmeter V connected to its terminals, the primary winding, of course, being open circuited. It will be observed that the voltmeter current is included in the milliammeter reading, but, as the impedance of the voltmeter will, as a rule, be considerably greater than that of the transformer, and as the currents in the parallel circuits differ in phase, the results will be very fairly accurate if the voltmeter current is ignored. Having the saturation data as obtained in this manner, the errors of the transformer will be proved to be unchanged if, at any future time, one or two points on the saturation curve can be reproduced with close approximation.

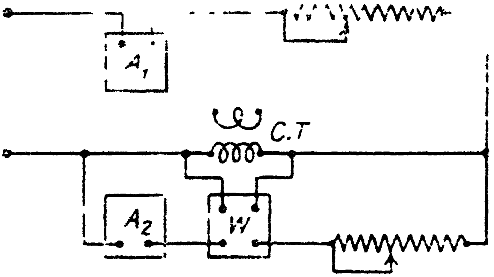


FIG. 18.—DETERMINING THE MAXIMUM VA OUTPUT OF A CURRENT TRANSFORMER

Testing the Maximum Volt-Ampere Output of a Current Transformer. The variation in the secondary volt-ampere output of a current transformer, with constant primary current and varying secondary impedance of unity power factor can conveniently be observed by the circuit illustrated in Fig. 18. Here the secondary winding of the transformer shunts an ammeter, the current coil of a wattmeter and an adjustable resistance, the voltage circuit of the wattmeter being connected to the secondary terminals, and the primary winding being open-circuited. The current in the external circuit is maintained at a constant value equal to the primary current at which the output is required divided by the turns ratio of the transformer. The maximum output can be observed with considerable precision on the wattmeter, and the impedance giving the maximum output will evidently be equal to W/I^2, where I is the wattmeter current.

Testing Windings for Protective Current Transformers.—It will be seen later that it is highly desirable to test the operation of protective gear by the application of artificial fault currents to the circuit in which the gear is installed. As with modern armour-clad switchgear it is generally impossible to obtain access to the primary terminals of high-tension current transformers, these transformers are sometimes furnished with an auxiliary primary winding with a number of turns of the same order as that of the secondary, into which test current can be passed from a low-pressure source. The effect of the test current in the auxiliary winding is very nearly the same as that of equivalent current in the primary, and with bar primary transformers the correspondence is exact if the auxiliary winding is uniformly distributed on the core.

It may be noted that if the auxiliary winding is so proportioned that it forms, with the secondary winding, a transformer of unity ratio, the errors can be readily determined before installation in the manner described above.

Transformers for Balanced Voltage Protection. As we shall see later, certain systems of automatic protection make use of transformers, which are required to furnish an open-circuit secondary voltage exactly proportional to the current flowing in the primary conductor. We have already seen that, when the secondary circuit of a current transformer is open-circuited, the whole of the primary current is used to magnetise the core, and the graphical representation between primary current and secondary voltage will be given by the saturation curve of the transformer. With a current transformer of normal design, having a closed magnetic circuit, it is therefore impossible to obtain a secondary voltage which bears a constant ratio to the primary current. Such a constancy of ratio over a large range of primary currents can only be obtained when the reluctance of the magnetic circuit is constant. This constancy of reluctance is obtained by the use of air gaps. If the length of an air gap in a transformer core is considerable, the effective reluctance of the magnetic circuit will be affected by the presence of adjacent magnetic material, and when air gap transformers are used in armour-clad switchgear units, the small clearances between the transformer and the iron enclosure render *it difficult to obtain constancy of reluctance of the* magnetic circuit at heavy overloads owing to leakage of the flux across the gap into the ironwork enclosure.

A balanced voltage transformer in which these difficulties are overcome must have its magnetic circuit constructed with a number of narrow air gaps in series, so that the tendency of gap flux to fringe is minimised. Fig. 19 represents the end view of the core of such a transformer as developed by the Metropolitan Vickers Electrical Co., in which it will be seen that there are eight air gaps in series in the magnetic circuit. The segments of the core are maintained in correct relative position by being bolted between non-magnetic end plates. The secondary voltage of this type of transformer is very nearly proportional to the primary current up to 10,000 ampere-turns.

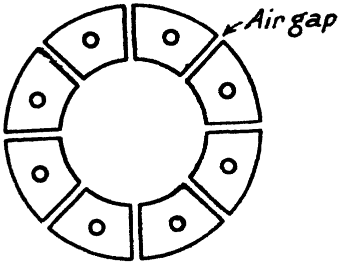


FIG. 19.—CORE OF AN AIR GAP CURRENT TRANSFORMER.

The characteristics of balanced voltage transformers under heavy overload conditions are difficult to test directly, unless facilities for obtaining high values of the testing current are available. A useful approximation to the actual characteristic is given by the saturation curve of the transformer, with secondary current excitation. By this test the value of the secondary current at which the impedance begins to decrease due to saturation of the iron can be readily observed, and this value multiplied by the number of secondary turns will give the approximate value of the primary current up to which the curve of secondary voltage is linear.

Voltage Transformers—As the primary winding of a voltage transformer is supplied at a voltage which is sensibly constant in normal conditions, the theory underlying its operation is generally the same as that of a power transformer.

The simplified vector diagram for a power transformer is shown in Fig. 20. I_s is the vector of secondary current lagging on the secondary voltage V_s by an angle ϕ. The primary voltage V_p is obtained by vectorially adding to V_s the components $I_s r$ and $I_s x$ of the drop in the transformer. These components are respectively in phase and in quadrature with I_s, and r and x are respectively the equivalent resistance and reactance of the transformer.

This simplified diagram is applicable to a power transformer when handling its rated full load as in these circumtsances the exciting current is a relatively small fraction of the total exciting current. With a voltage transformer the exciting current is comparable in magnitude with the component of the primary current supplying the secondary output. The exciting current circulates in the primary winding only, but it will give rise to a pressure drop which will decrease the residual voltage available for transformation. If the primary impedance be assumed to be one-half the total equivalent impedance of the transformer, the effect of the exciting current flowing in the primary circuit only can be considered the same as that of a current, one-half of the exciting current, supplying the secondary output. The vector diagram Fig. 21 (a) applies to a voltage transformer supplying an inductive burden, while Fig. 21 (b) applies to the transformer supplying a non-inductive burden. In this diagram I_e is equivalent to one-half the exciting current, and lags on V_s by an angle β, equal to the actual lag of the exciting current on V_p. The vector of I_e compounded

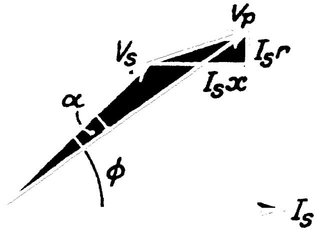


FIG. 20.—VECTOR DIAGRAM FOR A POWER TRANSFORMER

with that of I_s, gives the resultant vector I_1 of a *fictitious* secondary current the effect of which would give a voltage drop in the transformer approximately equal to that set up by the actual load current together with the exciting current. From these diagrams it will be seen that, with a highly inductive burden, the vector of secondary voltage leads in that of primary voltage. When the burden is non-inductive, as in Fig. 21 (b), the secondary voltage is seen to be lagging.

The errors of voltage transformers, in normal conditions, are from the point of view of protective gear operation negligibly small, and call for no detailed consideration. We may, however, observe that, as the primary winding consists of a very large number of turns, compensation for ratio error, with a stipulated burden can be made with great exactness by the removal of a certain number of turns. It is evident from the vector diagrams that the phase error of a voltage transformer disappears when the phase angle of the equivalent burden is equal to that of the transformer impedance. It is therefore possible, by connecting in parallel with the secondary burden, an additional impedance having the correct characteristic, completely to eliminate the phase error of a voltage transformer.

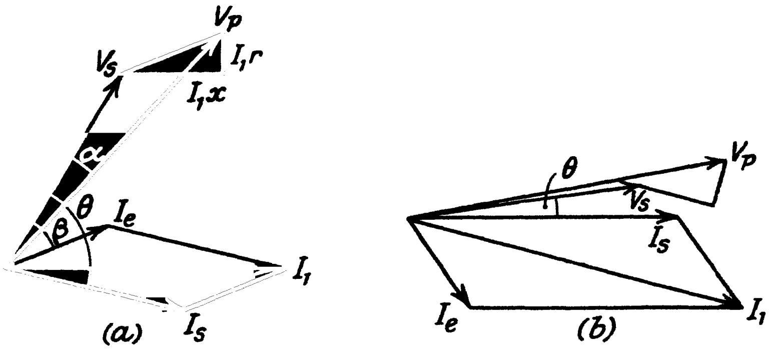


FIG. 21 —VECTOR DIAGRAMS FOR A VOLTAGE TRANSFORMER

Voltage transformers used for the operation of protective relays will, in fault conditions, be called upon to deal with voltages much smaller than the rated value. If the exciting current of a voltage transformer is proportional to the applied primary voltage then the vector diagram for a reduced voltage will geometrically be exactly similar to that applicable to normal conditions, and the fractional ratio error and the phase error will be unaltered. The proportionality of exciting current to applied voltage does not, however, obtain, and when this applied voltage falls below a point corresponding to maximum permeability of the material of the core, the decrease in exciting current for a further decrease in voltage will be relatively less than the decrease in load current. At very low voltages the length of the vector I_e will therefore tend to bear a greater ratio to that of I_s than in normal conditions, and accordingly the accuracy of transformation will be impaired. The increase in the fractional error of a voltage transformer at low voltages is not as a general rule greater than one per cent., and, from the point of view of the operation of protective relays this change in ratio error can be neglected.

The consideration of the transformation of three-phase voltages will be deferred at the moment, as the subject is more conveniently dealt with in the chapter covering the interconnection of protective transformers.

Capacitor Voltage Transformers.—An electromagnetic voltage transformer of the ordinary type is necessarily a fragile and expensive piece of apparatus for the transformation of very high voltages and, on the grounds of economy and reliability switchgear designers generally endeavour to avoid the use of these transformers as far as possible. A secondary copy of the phase to earth voltage of a high pressure conductor can be obtained by means of a condenser potential divider, but, unless the total capacitance is considerable, the component secondary voltage will only be correct for a negligible burden, and considerable ratio and phase errors will occur if an appreciable current is taken from the tapping point.

The capacitor voltage transformer is a device whereby, with a condenser potential divider of moderate capacitance, the voltage on a secondary burden is practically independent of its impedance. This constancy of secondary voltage is obtained by the use of a reactance in the circuit parallel to the earthed section of the potential divider. Resonance of this reactance with the capacitance in parallel causes the voltage on the capacitance to rise automatically as the burden impedance is reduced so that the voltage on this burden always remains sensibly constant.

The diagram of connections of a typical capacitor voltage transformer current is shown in Fig. 21A (a). Connected in parallel with the earthed section of a condenser potential divider is a circuit comprising a reactor and a double wound transformer which supplies the secondary burden. The transformer is used merely to isolate the secondary burden and to allow of adjustment of the secondary voltage irrespective of the exact ratio of the condenser ratio. The circuit is evidently equivalent electrically to that shown in Fig. 21A (b).

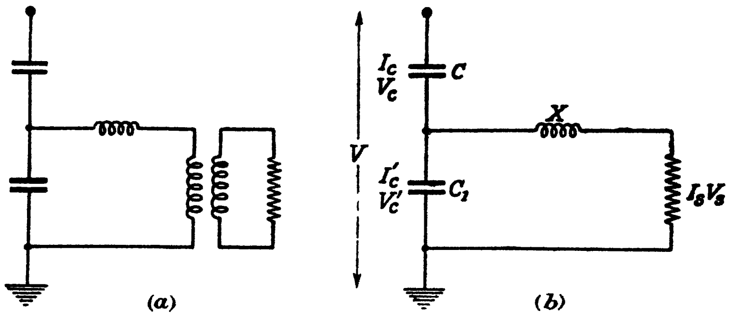


Fig 21A—Capacitor Voltage Transformer

The complete theory of the capacitor voltage transformer is somewhat complicated, but a good general understanding of this theory will be obtained by a careful study of the vector diagram, Fig. 21B, which applies to a secondary burden of unity power factor. Considering first the full-line vectors, I_s and V_s represent the secondary current and the voltage on the secondary burden. Compounding with V_s the drop in the

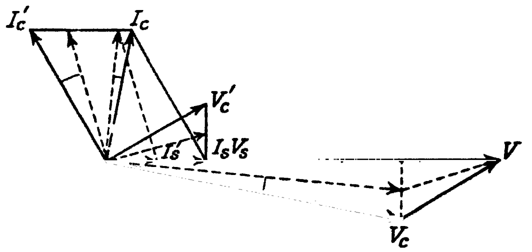


Fig 21B—Vector Diagram for Capacitor Voltage Transformer

reactance we obtain V_c^1, the vector of the voltage on the earthed section of the condenser potential divider. The current I_c^1 in this section leads V_c^1 by 90 degrees. The resultant of I_c and I_s is the current in the second section of the condenser, I_c. The voltage on this second section is represented by the vector V_c, lagging I_c by 90 degrees. Finally, the resultant of V_c and V_c^1 gives V, the primary voltage, which, due to the electrical constants of the circuit, is in phase with the secondary voltage V_s.

Suppose, now, that the impedance of the secondary burden is doubled and that the secondary voltage remains unchanged in magnitude and phase. The secondary current I_s^1 will have one half its former value, and the drop in the reactance will also be halved. The conditions are now represented by the dotted-line vectors, and a little study of the geometry of the diagram will show that the new vector V_c will assume such a position that, compounded with the new vector V_c^1, it will reproduce the original primary voltage V.

An independent unit may be used for the condenser potential divider, but it is customary to use the bushing of an oil current breaker or power transformer terminal by adding a condenser sheath to the outer layers of insulation and providing a tapping terminal. The reactance is usually incorporated in the double wound transformer and is adjustable by variation of the air gap of a magnetic shunt. Tappings are provided on the secondary winding so that the required secondary voltage can be obtained.

Polarity Markings of Current and Voltage Transformers.—The rules for marking the polarities of current and voltage transformers are laid down in B.S. Specification No. 81. According to these rules the same sequence of index marks represents the same direction of the induced E.M.F s in the circuits to which these marks apply. For current transformers the standard marks are M and L for the primary and Ⓜ and Ⓛ for the secondary. The primary and secondary windings of single-phase voltage transformers are respectively V+ and V, and $\textcircled{\scriptsize V+}$ and Ⓥ. Three-phase star/star voltage transformers bear the marks A, B, C and N for the primary and Ⓐ, Ⓑ, Ⓒ and Ⓝ for the secondary.

In Fig. 22 (a) is shown a voltage transformer marked in accordance with the standard convention. The full line arrows show the directions of the E.M.F.s induced in the two windings at any instant. The dotted arrow shows the direction of the applied voltage in the primary winding at the same instant. In Fig. 22 (b) the primary and secondary windings are shown joined in series, terminals of unlike markings being connected together. It will be seen that if a voltage is applied to the series combination, the drop across either component is less than the applied voltage. This is given in the B.S. Specification No. 81 as a criterion to determine the correctness of the marking. It is very convenient for transformers in which the ratio is small. When the ratio is large, the voltage drop across the high-pressure winding will differ so little from the applied voltage that it may be difficult to determine which of these voltages is the greater.

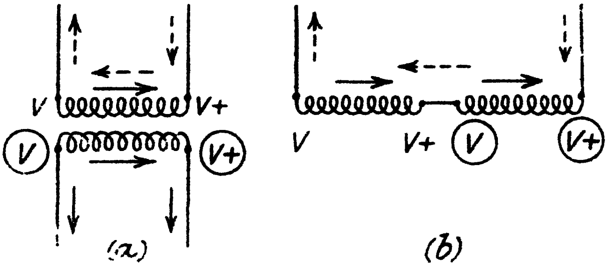
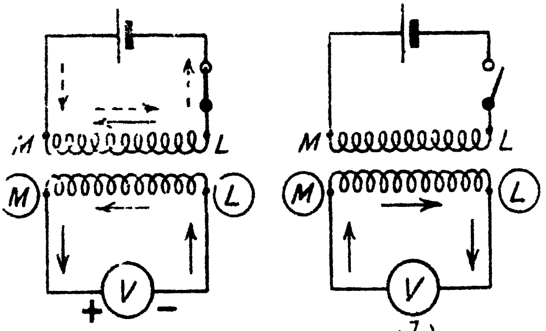


FIG 22.—ILLUSTRATING THE METHOD OF MARKING THE POLARITIES OF INSTRUMENT TRANSFORMER WINDINGS

Returning to Fig. 22 (a), it is seen that the terminal marking is so arranged that, if the ratio of the transformer were unity, and the transformer were cut out of circuit, and primary and secondary leads joined together in pairs taken from terminals with similar markings, the direction of the current in the secondary circuit would be unchanged.

A convenient method of checking the correctness of transformer terminal markings will be readily understood by a consideration of Fig. 23. Here is shown one winding connected through a switch to a source of direct current, and the other winding connected to a moving coil voltmeter. If, on making the direct current circuit, a forward kick is obtained on the voltmeter, the transformer terminals joined respectively to the positive pole of the D.C. supply and to the positive pole of the voltmeter should bear similar markings. The reason for this rule will be easily followed by a study of the diagram in which the induced E.M.F. are shown by full line arrows and the applied voltage from the D.C. source by a dotted arrow. When



(a) (b)

FIG. 23.—CHECKING THE POLARITY MARKINGS OF INSTRUMENT TRANSFORMERS

the D.C. supply is interrupted, the flux in the core disappears, the direction of the induced E.M.F.s reverses, and the voltmeter pointer shows a backward kick. The rule for applying this test can be stated in another form by saying that, if the terminal marking is correct, the deflection of the voltmeter pointer on making the D.C. circuit will be the same as if wires joined to similarly-marked terminals were joined together.

Both current and voltage transformers can be tested by the method just described. The voltmeter should be connected to the winding having the greatest number of turns.

CHAPTER III

THE INTERCONNECTION OF CURRENT AND VOLTAGE TRANSFORMERS

As a current or voltage transformer provides, in a completely insulated circuit, a current or voltage bearing a fixed ratio to the current or voltage in the main circuit in which it is connected, it is possible, by suitable interconnection of the secondary windings of such transformers connected in a two- or three-phase circuit, to obtain resultant currents or voltages which correspond to the vector addition or subtraction of the corresponding currents or voltages in the main primary circuit. The operation of many systems of automatic protection depends upon methods of interconnecting current transformers whereby no current appears in one part of the circuit except on the occurrence of a fault. We proceed now to a detailed study of the various methods of interconnecting protective transformers. The first stage of this study is concerned with the results of the interconnection of transformers which are assumed to be free from errors in all conditions of loading. The second stage is concerned with an examination of the effects of errors of transformation on the conditions as deduced on the assumption of perfect transformation. This part of the subject is one of considerable complexity, and, due to the fact that the errors of instrument transformers cannot be expressed by a rational formula, it is not possible to obtain more than general indications of the effect of these errors on the currents or voltages in the circuit arising from the interconnection of the transformers.

Star Connection of Current Transformers in Three-phase Circuits.—By the use of two current transformers only, secondary currents can be obtained corresponding to each of the three line currents in a three-phase three-wire circuit.

The method of connecting two transformers to give the three line currents is shown in Fig. 24. The common return lead for the transformers in red and blue phases is seen to carry a current proportional to the resultant of the currents in these two phases. Since, in a three-phase three-wire circuit, any line current is equal and opposite to the sum of the other two, the common return lead of the circuit of Fig. 24 will carry a current proportional to, but opposite in direction, to the current in the white phase. If the circuit shown is part of a system with an earthed neutral, and an earth fault occurs in the circuit on the white phase line, on the side of the transformer remote from the supply, then manifestly no current can appear in any part of the secondary circuit. The three-phase system is now no longer three-wire, but four-wire, the earth return in

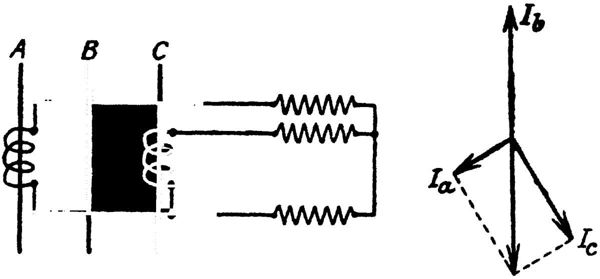


Fig 24.—Two Current Transformers in a Three-Phase Circuit.

this instance constituting the fourth wire. In order to obtain a secondary current corresponding to the primary current in the white phase line due to an earth fault, a third current transformer must be used, with its primary in the white phase, and its secondary connected to the place of common return for the red and blue phase transformer secondaries. Three transformers are shown connected [illegible] this fashion in Fig. 25. From this diagram it will be seen that a new common return wire has been added, so that the secondary system is a four-wire one. The reason for this must be clearly apprehended. Suppose the fourth wire to the common connection of the transformer secondaries be omitted, and primary current, due to an earth fault, flows in one only of the primary windings. The secondary circuit for the current transformer in this line now comprises the secondary windings of the other two transformers in parallel, and the secondary current must flow through these windings. As the primary windings of the transformers in the lines not carrying current are open-circuited, the burden of the third transformer will comprise the open-circuit secondary impedances of the idle transformers. We have seen that these open-circuit impedances are of an order very much greater than that of the normal burden of a current transformer. The secondary current delivered by the transformer whose primary is carrying current will therefore be very low. When the fourth common return wire is added, as shown in Fig. 25, there is a low impedance path for the secondary current of any one transformer, and this current will then be representative of that in the primary of the transformer.

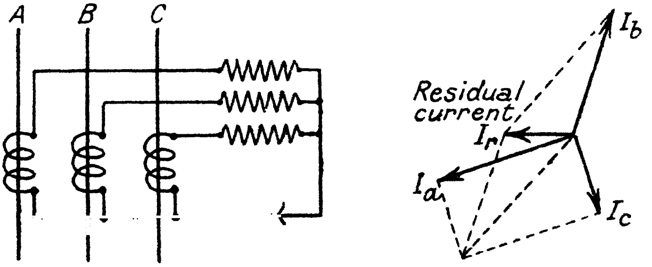


Fig. 25.—Three Current Transformers in a Three-Phase Circuit

When the circuit is free from earth faults, the algebraic sum of the three line currents is known to be zero at all times. The secondary currents of all three transformers can be conceived to be flowing simultaneously in the fourth or common return wire, and, as these currents are in phase with, and all bear the same ratio to the primary currents, their sum will also be zero at all times, and the current in the common return will be zero.

The absence of current in the fourth wire of the circuit considered applies to all conditions in the main circuit, so long as this circuit is three-wire, and that no current flowing in one line returns to the supply, either through earth or through a fourth wire in the main circuit. The absence of current is not dependent upon the currents in the main circuit being balanced. That this is the case can be readily understood by considering the extreme case of unbalance, that of single-phase current in two lines only. In this case the secondary currents of the current transformers in these two lines will evidently be equal and opposite, and, if these currents be conceived as flowing simultaneously in the fourth wire, their resultant will be zero.

If, however, the instantaneous sum of the three line currents ceases to be zero, due to an earth fault, the conditions will be as illustrated in the vector diagram of Fig. 25. Here, the three vectors of line currents do not cancel, but give a resultant I_r. This resultant will flow in the fourth wire of the secondary system, and is known as a residual current.

Here, then, we have the first example of an interconnected

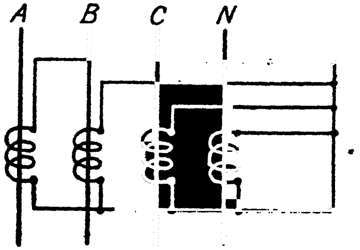


Fig. 26.—Four Current Transformers in a Three-Phase Four-Wire Circuit.

system of current transformer secondary windings, in which one component of the system only carries current in abnormal circumstances when a circuit, nominally three-wire, becomes, through the incidence of an earth fault, four-wire. The circuit shown in Fig. 25 is used extensively for what is usually known as leakage protection, a relay connected in the fourth wire being, except for current transformer imperfections, unresponsive to overloads or short-circuits between phases, but answering to a high degree of sensitivity to earth faults.

A system of interconnection similar to that shown in Fig. 25, but applicable to three-phase four-wire circuits is shown in Fig. 26. Here, it will be seen, a fourth current transformer has been connected in the fourth wire of the system, and a common return wire provided so that the complete secondary system is five-wire. It will be readily understood that with a current flowing in one phase and returning through the neutral main, no current will appear in the fifth or common return of the current transformer secondary network.

Delta Connection of Current Transformers.—The delta connection of three current transformers in a three-phase circuit is shown in Fig. 27. Each of the three leads from the common connection of two transformer secondaries will be observed to carry the difference of the secondary currents of these two transformers. The vector diagram for a balanced system of currents shows that each resultant current is √3 times the current in the transformer winding, and is displaced 30 degrees in phase with respect to each of the line currents of which it is compounded.

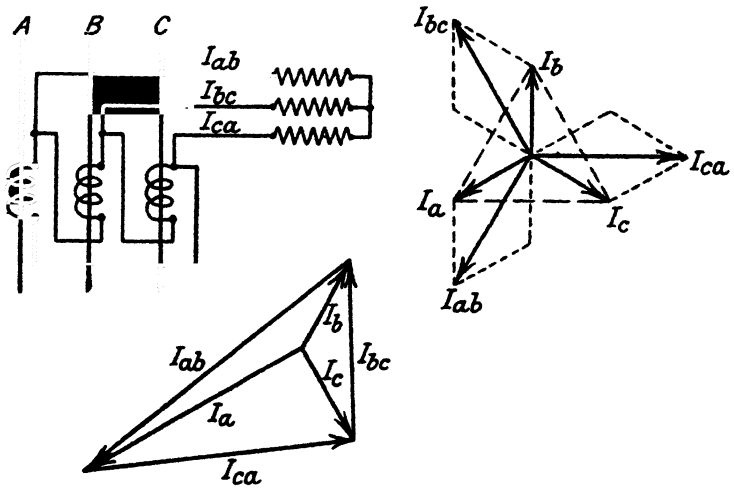


Fig 27.—Delta-Connected Current Transformers

The vector diagram for an unbalanced load is also shown in Fig. 27, and, from an examination of this diagram, it will be seen that the vectors of the resultant currents flowing from the delta form a closed triangle, which is formed by joining the extremities of the vectors of the line currents. Of these resultant currents, therefore, any one is the reversed resultant of the other two, and this applies, whether the main circuit is three-wire, or due to an earth fault, temporarily four-wire. This is a very important result, which will be referred to hereafter.

As the currents flowing from the delta are, with a balanced system of primary currents, equal to $\sqrt{3}$ times the secondary current of the transformers, any apparatus connected outside the delta must, for five-ampere current transformers, be wound for a maximum current of 8·66 amperes.

It is a characteristic of the delta method of connecting current transformers that a current in any one of the three lines of the main circuit will cause a current to appear in one of any two of the leads carrying current from the delta. Response to either short-circuit, earth fault, or overload conditions can be obtained by the use of two relay elements only connected in any two of these leads. An alternative connection of current transformers which secures this result is shown in Fig. 28. This method is usually known as the Z connection. Each of the relay windings carries the vector sum of two line currents, so that a current in any line will be reproduced in one of these elements. It will be seen from the accompanying vector diagram that, with a balanced load, the current in each of the relays is equal to that in the current transformer secondary windings, and such relays will therefore be designed for a rated current of five amperes. The diagram indicates the method of connecting a watthour meter in the Z network so as to secure a correct association of currents and voltages in the meter.

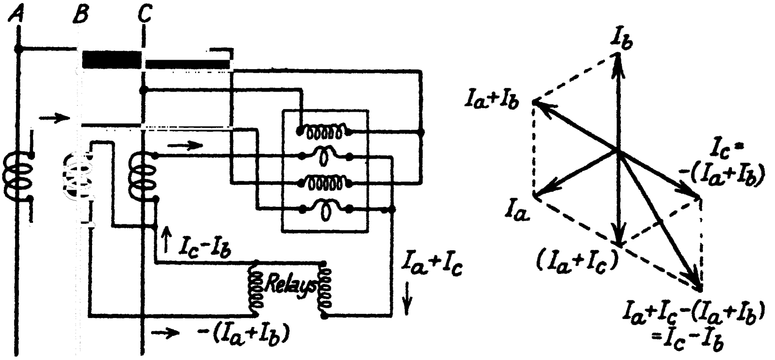
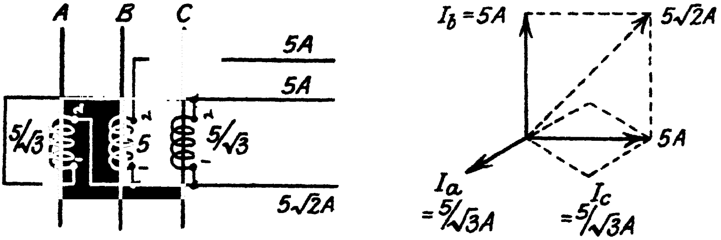


FIG. 28.—Z CONNECTION OF CURRENT TRANSFORMERS.

Three- to Two-phase Transformation.—It is necessary, for certain purposes, to transform the three-phase system of secondary currents furnished by three current transformers into an equivalent two-phase system. The usual method of doing this is shown in Fig. 29, from which it will be seen that one phase of the two-phase system is identical with one phase of the three-phase secondary system. The second phase of the two-phase system is the vector difference of the currents in the remaining two phases of the three-phase system. Since this difference will, for a balanced load, be $\sqrt{3}$ times each of its components, the rated secondary current of the two transformers which are interconnected to give this difference will be, for a five-ampere secondary system, $5/\sqrt{3} = 2{\cdot}89$ amperes. The two-phase currents will then each be five amperes, when the main three-phase primary lines carry their rated current.



G 29.—Three- to Two-Phase Connection of Current Transformers

The Interconnection of Voltage Transformers.—For electrical measurements a secondary system of three-phase voltages is usually obtained either by the open-delta or V connection of two single-phase voltage transformers, as shown in Fig. 30, or by the use of a three-phase voltage transformer, connected star/star, as shown in Fig. 31. The secondary voltages between phases, with either of these methods of interconnection, gives a true representation of the primary line voltages in all conditions. Three-phase voltage transformers used for electrical measurements are generally of the core type, and, due to the well-known properties of this type, the secondary neutral or the common connection of the three secondary windings gives a valid representation of the potential of the neutral of the primary system in which the transformer is connected, as long as this primary neutral carries no current. The secondary voltages between phases and neutral are therefore proportional

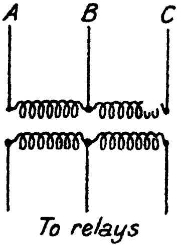


FIG. 30.—V CONNECTION OF SINGLE-PHASE VOLTAGE TRANSFORMERS

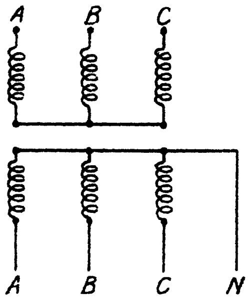


FIG. 31.—THREE-PHASE VOLTAGE TRANSFORMER

to the primary phase voltages. The three primary line voltages can appear as star voltages on the secondary side by the use of a delta-star voltage transformer, as shown in Fig. 32.

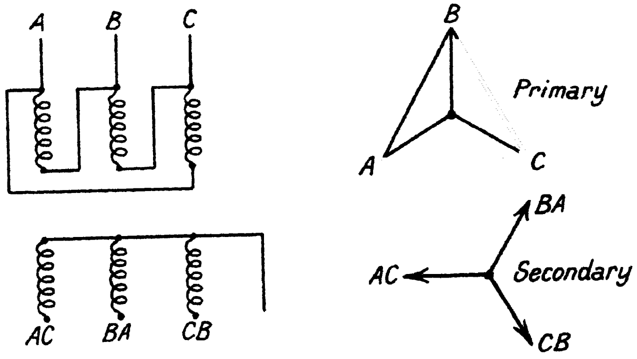
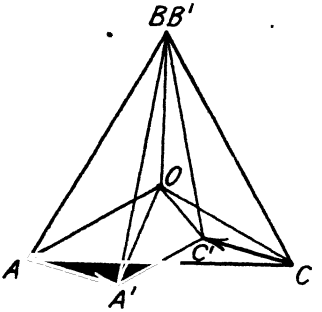


FIG. 32.—DELTA-STAR THREE-PHASE VOLTAGE TRANSFORMER

If the neutral of a three-phase system is earthed, then, as long as the system remains three-wire, the centroid of the triangle of voltage vectors at any point on the system will correspond to earth potential, however unbalanced the load carried by the system may be, provided all lines are of equal impedance. That this is the case will be evident from the consideration that, as the vectors of the line currents form a closed triangle, the vectors of line voltage drops will likewise form a closed triangle. Subtracting from the symmetrical system of E.M.F. generated by the alternators, these line drops, we obtain a resultant triangle of voltage vectors whose centroid is identical with that of the original triangle. This point is illustrated in Fig. 33, which shows the unbalancing effect of single-phase loading. It therefore follows that if the primary windings of three single-phase voltage transformers be star-connected, with the star point earthed as shown in Fig. 34, the vectors of secondary voltages will form a closed triangle,



ABC	Voltage system at source.
AA^1, CC^1	Vectors of line drop due to single-phase load.
$A^1B^1C^1$	Resultant voltage system at load.
O	Common centroid of ABC and $A^1B^1C^1$.

FIG. 33.—THE UNBALANCING OF A THREE-PHASE VOLTAGE SYSTEM BY A SINGLE-PHASE LOAD.

and if the secondary windings be connected in delta with one point open, no voltage will be found across this open point. If, due to an earth fault, the main system becomes four-wire, the vectors of voltage drop, being proportional to the line currents, will no longer form a closed triangle. The same condition will apply to the vectors of the phase voltages to earth, and the vector sum of these voltages, represented on the secondary side of the interconnection shown in Fig. 34 by the voltage across the open point of the delta, will assume a value and phase depending upon the magnitude of the earth fault current and the impedance of the paths through which it flows.

This voltage, being the resultant of the three phase voltages, is evidently analogous to the residual current which appears in the fourth wire of the current transformer network shown in Fig. 25, and both residual current and residual voltage are due to the same cause, viz., an earth fault current.

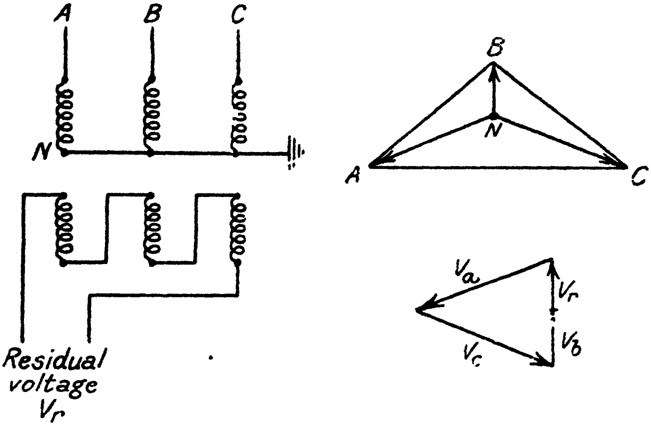


FIG. 34—VOLTAGE TRANSFORMER CONNECTION FOR RESIDUAL VOLTAGE.

The maximum value of the residual voltage occurs when one phase of the system is earthed at a position near to the voltage transformer, and the main earthing arrangements are such that the three-line voltages are relatively unaffected. This condition is shown in Fig. 35. It is seen that the transformer

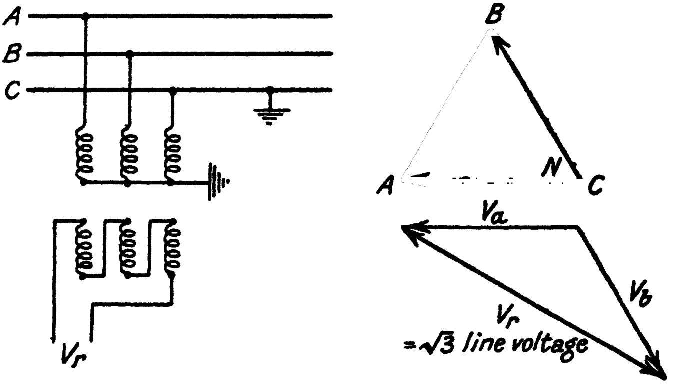


FIG. 35—ILLUSTRATING THE CONDITIONS FOR MAXIMUM RESIDUAL VOLTAGE.

connected to the faulty line is short-circuited, and that the other transformers have full line volts on their primary windings. The voltage V_r across the open point in the delta is seen to correspond to $\sqrt{3}$ times the line volts, or to three times the normal voltage on one of the secondary windings. If, therefore, the normal secondary voltage is 110, any relay connected in the delta must be designed for a voltage of 330 during short periods.

The residual voltage due to the unbalancing of the voltage system set up by an earth fault, cannot be indicated by a three-

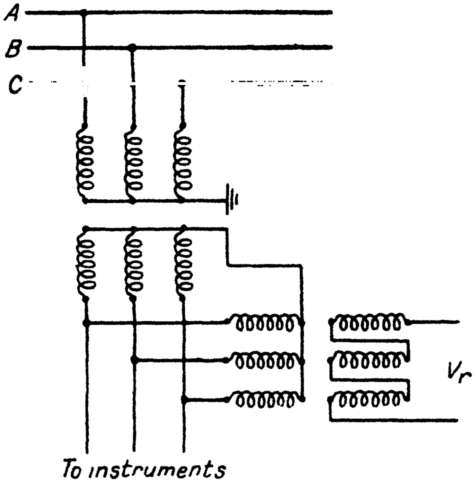


FIG 36.—OBTAINING A RESIDUAL VOLTAGE FROM AN AUXILIARY VOLTAGE TRANSFORMER

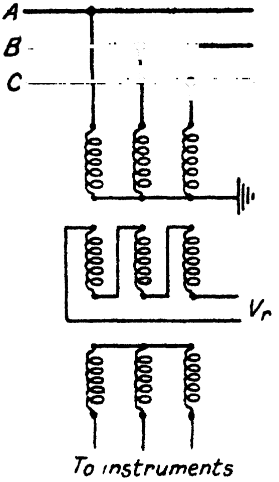


FIG. 37.—OBTAINING A RESIDUAL VOLTAGE FROM A TERTIARY DELTA WINDING

phase voltage transformer of the usual core type. This is because the magnetic circuit of such a transformer is what may be described as three-wire, in that, as there are three limbs only through which the flux circulates, the flux set up in any one of these limbs must find its return path through the other two If such a transformer is connected to a three-phase system, with the star point of its primary windings earthed, then the incidence of an earth fault in the system adjacent to the transformer will extinguish the voltage to earth on the faulty phase. There will be a voltage to earth on the other phases, and these voltages will set up fluxes in two of the limbs of the core The resultant of these fluxes will find a return path through the limb corresponding to the earthed phase, and this resultant flux will induce a fictitious voltage in the secondary winding corresponding to the earthed phase. The voltage across the open point of the delta of the secondary windings of the transformer will therefore not be the true residual voltage. For this residual voltage to be accurately reproduced on the secondary side of the transformer, a three-phase

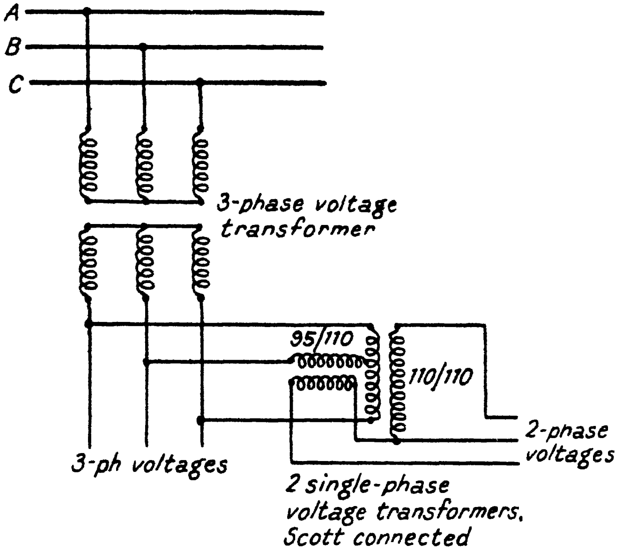

A
B
C
3-phase voltage transformer
95/110
110/110
2-phase voltages
3-ph voltages
2 single-phase voltage transformers, Scott connected

FIG. 38.—THREE- TO TWO-PHASE VOLTAGE TRANSFORMATION

transformer of the shell type, with independent magnetic circuits, or three single-phase voltage transformers, must be used. When it is desired to retain the ordinary star-connection of the voltage transformer secondaries for energising measuring instruments, the residual voltage can be obtained by a delta tertiary winding on the three-phase transformer, or by an auxiliary voltage transformer, having unity ratio, energised from the secondary side of the main transformer. These schemes of connection are indicated in Figs. 36 and 37.

The transformation of three- to two-phase voltages is not required for automatic protective systems so frequently as is the corresponding transformation for currents. Many systems can be devised for this transformation, the simplest being the well-known Scott connection. The application of this connection by the use of an auxiliary bank of transformers energised from the secondary side of a three-phase voltage transformer is shown in Fig. 38. The connections can evidently be so arranged that the secondary voltages on the two-phase side are in phase with the two-phase secondary currents given by the network shown in Fig. 29, when the main three-phase system is balanced and the power factor is unity.

Neutral Inversion.—Reference was made on page 63 to the abnormal pressures that can be imposed on the primary windings of star-connected voltage transformers with an earthed neutral point, in faulty conditions. These pressures are, of course, set up when the neutral of the source of supply is also earthed. There is another condition in which abnormal pressures on star-connected voltage transformers can appear; this is when the neutral of the supply source is unearthed, and the only earth-connection of the system is the neutral point of the transformer primaries.

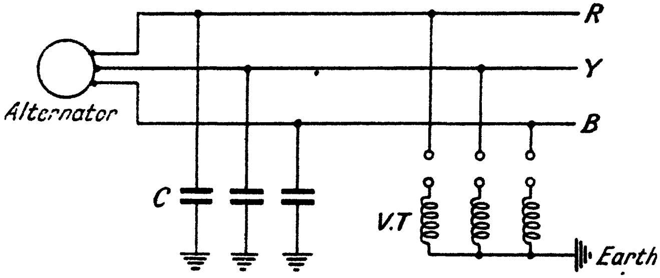


FIG. 38a.

Consider Fig. 38(a); here VT is a set of star-connected voltage transformers for an isolated alternator, the neutral terminal of which is not connected to earth. The only currents flowing from the machine are those in the lime capacitances, C to earth, and those in the transformer primaries. If all these primaries are connected to the main conductors, and the impedances of these three currents are equal and linear, then the load on the machine will be balanced, and in the vector diagram of line and star voltages, the point corresponding to the earthed neutral will be the centroid of the triangle of line-voltage vectors. Suppose, however, that one primary winding only is connected, say to Y line, the load in the machine will now be unsymmetrical, and will comprise the two equal capacitances of lines R and B, and the transformer winding shunted by a line capacitance, of line Y. Suppose that this parallel circuit has a resultant phase angle θ. Then it is easy to see that the position of the point O in the vector diagram of voltages, Fig. 38 (b), will line on the segment of a circle BOY, constructed on the median YD of the triangle of line voltage vectors RYB, and containing an angle equal to 90-θ, and that the voltages to earth of the three lines will be OR, OY and OB respectively. For taking any point O

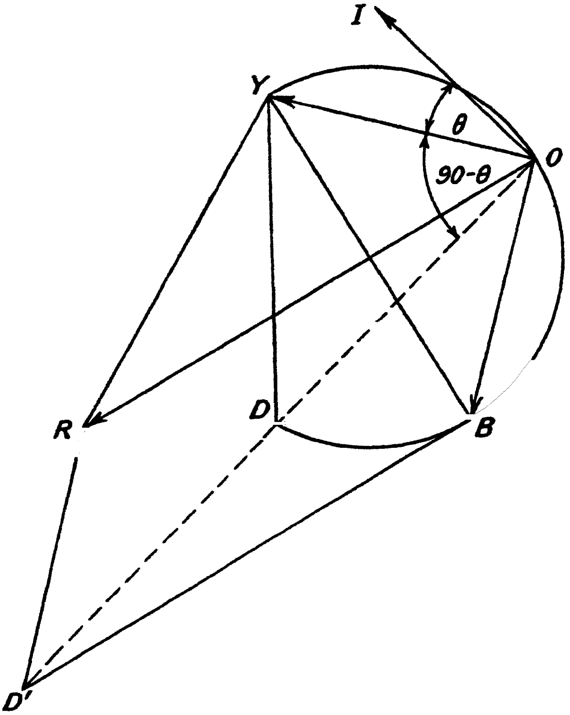


FIG. 38b

on the segment, the resultant of the currents in the R and B line capacitances will lead 90 degrees on the resultant OD of the corresponding line-to-earth pressures, and the reverse of this *resultant, OI, the current in the shunted transformer* winding will therefore lag the Y line-to-earth pressure, by the correct angle θ. The position of the point O on the segment will be determined by the condition that the ratio of OY to OD is equal to the ratio of the impedances of the shunted transformer winding to a line capacitance. The diagram is constructed for an angle of 30 degrees, and it is seen that the point O lies without the line-voltage vector triangle. This phenomenon is known as neutral inversion. In the condition shown, when $\theta=30$, it is easy to see that the voltage-to-earth of R line is greatest when OR passes through the centre of the circle of which BOY is a segment and that its value is then $\frac{1}{2}(\sqrt{3}+1)=1{\cdot}366$ times line pressure. As θ, corresponding to the reactive impedance increases, then regarding the point O corresponding to earthed potential as fixed, the line-voltage triangle RYB will move further and further to the left, and the possible values of the line-to-earth voltages will continually increase. It is not difficult to see that a somewhat similar condition can arise if two transformer windings only are connected to the main dondutors

So far we have assumed that the impedance of each transformer winding is linear, that is, the current in it is exactly proportional to the applied pressure. Actually, however, this is not the case, and because of magnetic saturation, the impedance tends rapidly to diminish after the applied pressure exceeds a value depending upon the design. The impedance characteristic of a parallel circuit comprising a transformer winding shunted by a capacitance is therefore, as regards reactive current, as shown in Fig. 38(c). The total current passing into the parallel combination is the difference of the lagging reactive current in the transformer and the leading current in the capacitance. This total current therefore varies with applied voltage in the manner shown by the curve OABC, and it is seen at once that in the region AB the impedance of the parallel circuit is unstable, in that a rise of pressure causes a diminution of reactive current. The consequence of this is peculiar ; when all three transformer windings of the circuit of Fig. 38(a) are connected, and, perhaps because of some transient condition, the impedance of the parallel circuits assumes an anomalous value corresponding to the region AB of the curve of Fig. 38(c), an unstable condition is set up, and the voltages-to-earth of the system take abnormally high values like those corresponding to the neutral-conversion conditions of Fig. 38(b). Oscillograph records show that the point O of the diagram of line and star pressures is not stationary but rotates relatively to the line-voltage triangle at speeds that may correspond to double or half the circuit frequency. This rotation is, of course, due to the distorted wave forms of the line-to-earth voltages; for as the currents in the star-connected load branches must be sinusoidal, the voltages necessary to produce them in branches of anomalously varying impedance must be very distorted. A diagram like Fig. 38(b), showing these voltages with a rotating neutral point O, is not a vector diagram, but merely a geometrical representation of the circuit conditions.

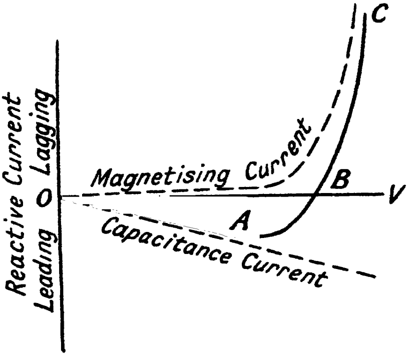


FIG. 38c.

This kind of neutral inversion, due to the peculiar character of the shunting of a non-linear reactive impedance by a capacitance, is evidently mitigated by loading the voltage transformers with resistance, for this is practically equivalent to resistance shunting and hence to the stabilising of the impedances of the star-connected circuits. This kind of stabilisation can be obtained without the imposition of a permanent resistance burden on the transformers by providing them each with a tertiary winding, as in Fig. 37 and by closing the delta connection of these windings, through a resistance. This resistance will then carry appreciable current only when, due to a tendency to neutral inversion the residual voltage tends to rise to an abnormally high value. The danger of this kind of neutral inversion is also reduced if the voltage transformers are so designed that their impedances are linear for pressures considerably in excess of the rated values. Of course, if the neutral of the supply source is earthed, the system, as regards the voltage transformers is virtually 4-wire, and no condition of instability can occur.

The Effect of Current Transformer Errors in Interconnected Circuits.—We have, so far, neglected the errors of current transformers when considering the compounding of secondary currents in interconnected circuits. We shall consider the effect of these errors in a very simple method of interconnection which, in various forms of development, is extensively used for the protection of electrical machinery. This circuit is illustrated in Fig. 39. Here the circuit is considered, for the sake of simplicity, to be single-phase. M is the winding of the machine to be protected, at each end of this winding is a current transformer, and the secondaries of the two current transformers are connected in series. The winding of a protective relay R is connected to the circuit in the manner shown. The elementary explanation of the circuit is that so long as there is no fault in the primary circuit between the two current transformers, the primary windings of these transformers carry equal currents. The secondary currents will also be equal, and these currents will circulate in the main secondary circuit, while there will be no current in the relay winding. If a fault

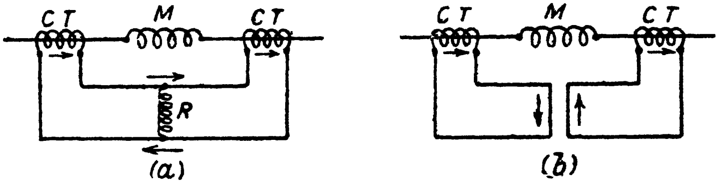
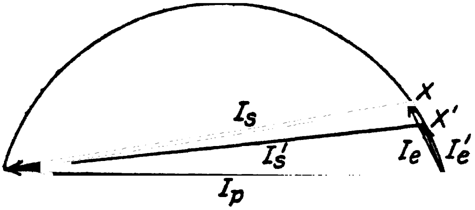


FIG 39—ELEMENTARY DIFFERENTIAL CIRCUIT

occurs in the primary circuit between the two transformers, one of these transformers will carry a primary current greater than the other. This difference will be reproduced in the secondary circuit, and the difference between the secondary currents of the two transformers will flow in the relay winding. With transformers having no errors it is easy to comprehend the non-appearance of current in the relay in normal conditions, since this relay can be conceived as carrying two exactly equal currents flowing in opposite directions.

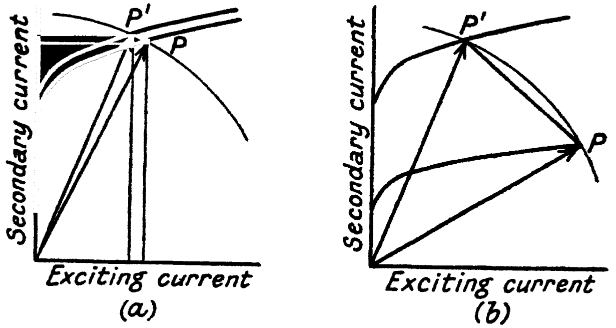
The effect of current transformer errors on the behaviour of this circuit is two-fold. In the first place these errors usually result in the appearance of a current in the relay winding when the primary currents are identical. This relay current will be small with normal values of the primary current, but may increase to such a value as will operate the relay if the equal values of the primary current rise to excessive values due to faults external to the apparatus protected. Secondly, the effect of transformer errors is to make the actual value of the current in the relay less than that indicated by the nominal ratio of transformation.



I_p = Common Primary Current.
I_s, I_s^1 = Secondary Currents.
I_e, I_e^1 = Exciting Currents.
XX^1 = Vector difference of exciting currents.

FIG 40 —VECTOR DIAGRAM FOR FIG 39.

The appearance of current in the relay winding with equal primary currents is manifestly due to a difference in the errors of the current transformers. Let us consider the arrangement shown in Fig. 39 (b), in which the two secondary circuits are isolated. The difference between the two secondary currents will evidently be equal to the current which would appear in a relay connected as shown in Fig. 39 (a) with negligible impedance. If we assume that the secondary impedance, and the phase angle between the vectors of secondary and exciting currents in the two transformers is the same, the vector diagrams for these transformers can be exhibited in the manner set out in Fig. 40, where the points X and X^1 of the vector triangles lie on a circle, since the angles at these points are assumed to be equal. From this diagram it is evident that if the magnitudes of I_e and I_e^1 are small as compared with the secondary currents, *then the difference in these secondary currents*, represented approximately by the arc XX^1, is very nearly equal to the difference in the exciting currents for voltages corresponding to I_s and I_s^1. As the secondary currents are nearly equal, and the secondary impedances the same, the



(a) (b)

FIG. 41 —GRAPHICAL CONSTRUCTION FOR DIFFERENCE OF SECONDARY CURRENTS IN FIG. 39

difference between these currents, which would flow in a relay of negligible impedance, is equal to the difference in the exciting currents for equal voltages.

If the secondary impedance and the primary current have such high values that the exciting current becomes comparable in value with the secondary current, due to saturation of the iron of the transformers, the conditions can be studied by consideration of Fig. 41 (a). Here are plotted the saturation curves of the two transformers for high flux densities, and the scale of vertical ordinates is such that these ordinates, for the equal secondary impedances, represent secondary currents to the same scale as the horizontal ordinates representing exciting currents. If we assume that the secondary currents and the exciting currents are in phase quadrature, then an arc of a circle with a given primary current, reduced to a secondary value, will cut the saturation curves in two points P and P_1. It is easy to see that the arc PP^1 is approximately equal to the vector difference between the two secondary currents, and that, if the two saturation curves become approximately equidistant, this difference in the secondary currents tends to a limiting value, which depends upon the saturation voltages of the two transformers. The construction in the diagram can evidently be modified for cases in which the phase difference between the vectors of secondary and exciting currents differs from 90 degrees, by plotting the saturation curves with oblique co-ordinates, and in such a case, the value of the difference between the secondary currents will also tend to a limiting value.

If the values of the secondary impedances of the two transformers are not the same, then, in order to carry out the graphical construction of Fig. 41, it will be necessary to adjust the scale of the vertical ordinates of one of the saturation curves. If, for instance, the impedance of the secondary circuit of one of the transformers be only one-half that of the other, a given secondary current in the transformer having the lower impedance will only require one-half of the voltage that the same current will require in the other transformer. The two saturation curves will then be plotted as shown in Fig. 41 (b), from which it is seen that the difference in the secondary currents is very greatly increased.

The foregoing discussion shows the order of the current which may be expected to be found in the relay windings of the circuit shown in Fig. 39, when the impedance of the relay is negligible. It is evident that the value of the relay current will depend upon the value of the relay impedance, and that the relay current will tend to zero as the relay impedance increases indefinitely. Let us now consider the circuit shown in Fig. 42. The conditions are now the same as shown in Fig. 39, when the impedance of the relay is infinite. We now have the primary and secondary currents equal in both transformers, and if the difference in phase of secondary and exciting currents and the number of turns be assumed to be the same, the exciting currents will also be the same in the two transformers. Unless the saturation curves are identical equal exciting currents will produce unequal secondary E.M.F.s.

The voltage required to drive the secondary current through the secondary circuit will thus be divided unequally between the two transformers. The division of the total secondary voltage is illustrated in Fig. 43. At (a) we have shown the condition when the total secondary voltage is shared equally between the two transformers, this voltage being plotted against secondary impedance. The diagram shows that points in the circuit which divide the secondary impedance equally, have no potential difference between them. If the saturation curves of the transformers differ as shown at Fig. 41, there will be a potential difference at these points which is equal to one-half the difference of the secondary voltages. If the difference between the secondary voltages tends to a constant value at saturation, as shown in the curves in Fig. 41 (a), then the potential difference between the two points in the secondary circuit of Fig. 42, dividing the impedance equally, will also tend to a constant value. If a relay be connected between these points, and the impedance of the relay be considerable, then the current in such a relay may also be considered to tend to a limiting value at saturation.

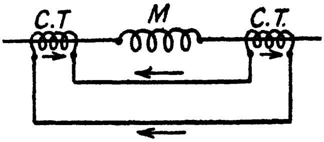


FIG. 42.—DIFFERENTIAL CIRCUIT WITH INFINITE RELAY IMPEDANCE.

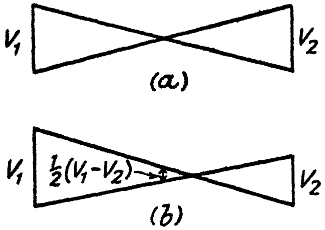


FIG. 43. ILLUSTRATING FIG 42

We have seen that the current in a relay connected as shown in Fig. 39, with equal primary currents, depends upon the relay impedance. It is also evident that the potential difference on the relay winding will also depend upon its impedance. The effect of connecting a relay to the circuit shown in Fig. 42 will be to reduce any potential difference between these points. We can therefore assign a maximum value to the value of the current in a relay connected, as shown in Fig. 39, to points in the circuit which divide the secondary impedance equally.

This value will be equal to one-half of the difference between the secondary voltages of the transformers at saturation divided by the relay impedance. If this maximum value is less than the current which will operate the relay, then no current in the primary circuit, however large, will affect the relay, provided that no fault exists in the part of the circuit between the current transformers.

Effect of Relay Impedance on Primary Operating Current.—Although, in the circuit shown in Fig. 39, we can reduce the relay current with high values of equal primary currents as much as may be desired, by increasing the relay impedance, this increase in impedance will manifestly affect the value of the difference in the primary currents required to cause operation of the relay. If we consider that the only current in the primary circuit of Fig. 39 is fault current flowing in one of the current transformer primaries, the burden of the transformer will evidently include the relay impedance. The secondary current furnished by the active current transformer will also be partly shunted into the secondary winding of the idle transformer. If the relay impedance is considerable in relation to the remainder of the secondary circuit, then the equivalent circuit may be taken to be as shown in Fig. 44. This circuit is based on the same conceptions as underlie the circuit originally considered on p. 17, and as in Fig. 44, the burden is shunted by two secondary windings in parallel, the errors of transformation will be of the order of twice those which would occur if the active transformer were connected to the relay only.

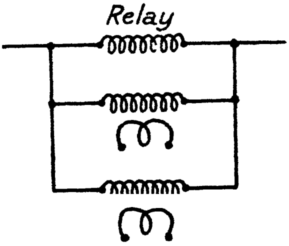


FIG 44 —EQUIVALENT CIRCUIT TO FIG 39.

If both transformers are carrying primary currents, and these currents, due to a fault, are unequal, the difference current required to produce the operating current in the relay can still be considered in reference to the equivalent circuit shown in Fig. 44. In this case, however, the transformer secondary windings, considered as impedances shunting the relay, are excited to a voltage equal to that required to circulate the secondary current corresponding to the smaller primary current through the two secondary windings, while the current applied to the parallel combination in the equivalent circuit will correspond to the difference in the primary currents. The shunting effect of the transformer secondary windings will therefore depend upon the differential impedance for the voltage corresponding to the circulating current, rather than the total impedance. A reference to Fig. 7 shows that the differential impedance of the transformer secondary windings is for moderate voltages much greater than the total impedance for zero voltage. The shunting effect of the current transformer secondaries thus diminishes at first as the value of the circulating current increases. When the voltage due to the circulating current approaches that of saturation the differential impedance rapidly diminishes, and the difference in the primary currents required to operate the relay rapidly increases. A typical curve showing the relation of difference, or fault, current to cause relay operation and circulating current is shown in Fig. 45.

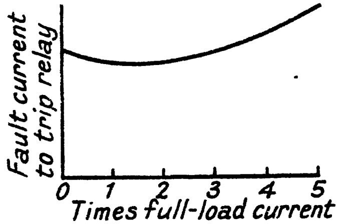


FIG 45.—VARIATION OF FAULT CURRENT TO TRIP RELAY IN FIG 39 WITH LOAD CURRENT.

This matter may be considered in another manner by a study of Fig. 46. We have here a saturation curve which we assume to apply to both transformers. If one of the current transformers carries no current, then the total secondary voltage of the other transformer when the relay is carrying its operating current will be made up of the voltage O_1P_1 on the relay, and P_1Q_1 the voltage drop in the secondary winding and in the connecting leads between the transformer and the points at which the relay is connected. The total exciting current to give this voltage will be A_1C_1. Due to the fact that the secondary of the second transformer shunts the relay, an exciting current, corresponding to O_1P_1 will pass into this transformer. The total exciting current which has to be supplied from the

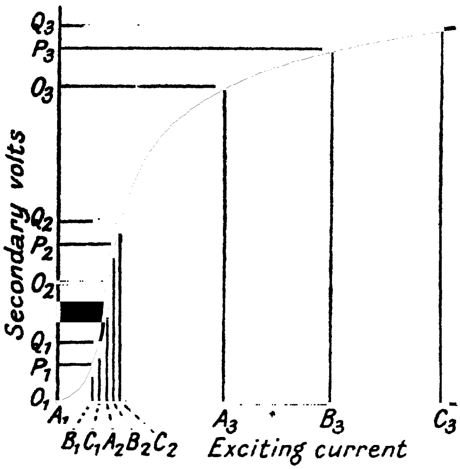


Fig. 46.—Illustrating Fig 45

primary current of the first transformer is thus $A_1B_1 + A_1C_1$. If the difference current in the one transformer, due to a fault, is superimposed on a load current common to the two transformers and the common secondary voltage due to the load current is O_1O_2, then the secondary voltage of the transformer carrying the fault current must increase from O_1O_2 to O_1Q_2, if sufficient current is to pass into the relay to cause it to operate. This increase in the secondary voltage will require an increase in the exciting current of $A_2B_2 + A_2C_2$, which is derived from the fault current. This exciting current is seen to be less than that required, when there is no load current in the primary circuit. If the load current assumes a high value so that the common secondary voltage due to this current assumes such a value as O_1O_3, then the necessary increase in the secondary voltage of the transformer carrying the fault current to give operation of the relay is seen to require a large additional exciting current equal to $A_3B_3 + A_3C_3$.

Modifications of the Differential Network.- There are several interesting modifications of the simple circuit shown in Fig. 42 which depend upon the general principles discussed above, and which, although properly belonging to the technique of automatic protective systems, may conveniently be considered here. In Fig. 47 we have a network due to the Asea Co. Each current transformer has two secondary windings, one pair of which are connected in series, so that the common secondary current circulates through them, and the other pair of secondary windings are connected in opposition, through the windings of a relay. Neglecting any current in this relay, we see that as primary and secondary currents are identical in the two transformers, the exciting currents will also be approximately equal. The voltage on the relay winding will therefore be equal to the difference between the voltages set up in the opposed windings of the transformers by the fluxes due to equal exciting currents. We have already seen, and a reference to Fig. 41 will remind the reader that, however great the primary current may be, the differences between the voltages induced in the opposed windings tends to a limiting value, and, provided the impedance of the relay is suited to this limiting value, the current in it, with equal primary currents, will never reach the operating value. If, due to a fault, the primary currents become unequal, the excess current will

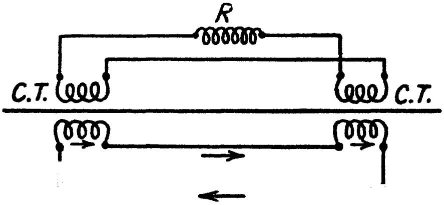


FIG 47 —A S E A DIFFERENTIAL CIRCUIT

induce a voltage in the auxiliary secondary winding of the corresponding transformer, and so give rise to operation of the relay.

Another interesting modification of the elementary differential network, due to the British Thomson Houston Co., has been evolved, primarily for the protection of transformers. Referring to Fig. 43 we have seen that, if the number of secondary turns on each transformer is the same, there will be no difference of potential between points in the secondary circuit which divide the total impedance approximately. Conceive now that the two transformers, while having identical ratios, have greatly differing numbers of primary and secondary turns. The approximately equal exciting currents will now give rise to differing secondary voltages, and the points of the secondary circuit between which there is no difference of potential may be inside the secondary winding of the transformer having the smaller number of secondary turns. This condition is illustrated diagrammatically in Fig. 48, in which one current transformer is assumed to have in both windings one-half the number of turns on the other.

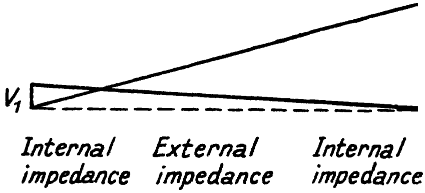


FIG. 48.—ILLUSTRATING THE B T.H. DIFFERENTIAL CIRCUIT.

The current shown in Fig. 49 has been evolved to avoid the difficulties which arise when the two transformers have a greatly differing number of ampere-turns. From this diagram it will be seen that the relay is connected to a tertiary winding on the transformer A which has the smaller number of ampere turns. Conceive now that the transformer B is free from errors and that rated current flows in each of the primary windings. The secondary current delivered by B will be exactly five amperes, and, as this current flows in the secondary winding of A, the primary and secondary ampere turns will exactly balance. There will then be no flux in the core, the burden on

A will be zero, and no E.M.F. can be induced in the tertiary circuit containing the relay. If there is a small error of transformation in A, there will be a corresponding difference between primary and secondary ampere-turns in B, and a flux will appear in the core which will induce a current in the tertiary circuit. The relay current for equal primary currents, however, depends upon the errors of B transformer, and if this transformer is so designed that, for the maximum current which can appear in the primary circuit, its errors are small, then the relay current will be determined by these errors, notwithstanding the ampere turns on A may be so small that with the maximum current and a normal burden its ratio would completely break down. The effect of the inductive coupling of the relay to the secondary circuit by means of the tertiary winding is thus to relieve the current transformer with the smaller number of ampere turns of practically the whole of its burden.

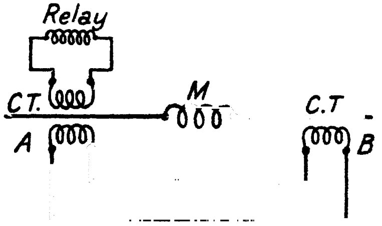


FIG. 49.—B T.H. DIFFERENTIAL CIRCUIT

The Effect of Transformer Errors in Residual Current Networks.—We have seen that a discussion of the result of current transformer errors in so simple an interconnection as shown in Fig. 42 is one of some difficulty. The effect of transformer errors in the residual current network shown in Fig. 25 is even more complicated, especially in the case of an excessive balanced system of currents in the primary conductors. Short-circuit currents in three-phase circuits are, however, usually between phases, and for a single-phase short-circuit, the network becomes similar to that illustrated in Fig. 42. This will be clear from a consideration of Fig. 50 in which we have shown at (a) the residual current circuit represented in the usual way, and at (b) in such a manner as to show the similarity of the circuit, for a single-phase short-circuit, to that illustrated in Fig. 42. If the short-circuit current flows in A and C lines, and there is no current in B phase, the relay current will depend on the considerations previously discussed, and will, in addition, be modified by the circumstance that it is shunted by the secondary winding of the current transformer in B line.

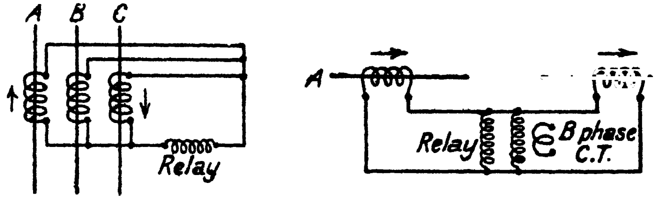


FIG 50.—RESIDUAL CURRENT NETWORK WITH SINGLE-PHASE SHORT-CIRCUIT.

When there is a residual current in the primary circuit, a corresponding current will appear in the relay, but in this case the relay will be shunted by the secondary windings of the current transformers in the other two phases. The ratio error of the transformation of the residual current will therefore be of the order of three times the ratio error of the current transformer when connected only to the relay winding. The effect of increasing the relay impedance with a view to reducing the relay current below the operating value with single-phase short-circuits will thus have a considerable effect on the ratio

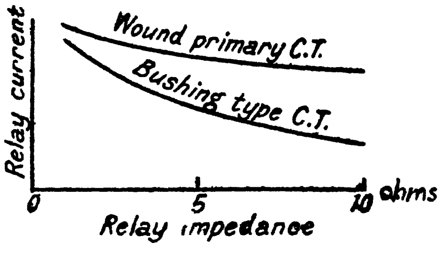


FIG 51 —EFFECT OF RELAY IMPEDANCE ON SECONDARY RESIDUAL CURRENT.

of transformation of residual currents. Typical curves showing the relation of relay current and relay impedance with a *fixed value of the residual current are shown in Fig. 51.*

A residual-current network may have a relay of very low or of comparatively high impedance. If the impedance is very low, the rates of transformation of primary earth-leakage or residual currents will be practically the same as that of the current-transformer rates, so that the actual operating current of the relay corresponds to its leakage-current setting in primary amperes. If the relay impedance is relatively high then, provided that the VA absorbed therein for operation is constant, the operating current value will vary inversely as the impedance. Thus if a low-impedance relay requires 1A at 1V for operation, a high-impedance relay of 20 ohms value will require 0·05A at 20V. The breakdown of residual-current transformation for a relay voltage of 20 may be so great that the primary fault current setting is not very different from that of the low impedance instrument. The behaviour of the relays in the condition of single-phase short-circuit will, however, be very different, and as the low-impedance relay requires only 1 volt to operate it, there will be much greater danger of the relay current approaching the operating value than there will for the high impedance instrument, the operating voltage of which will probably be at all times less than the fraction of the difference of the secondary E.M.F.s of the current transformers carrying the short-circuit, current which appears at its terminals which difference as has been seen on page 72 tends to a limiting value as the primary short-circuit current increases indefinitely.

The use of high-impedance relays for resisting-current protective networks is because of this immunity from being affected by single-phase short-circuits, tending to become common. It must be noted however that when a high impedance relay is used, its primary earth-leakage setting cannot be inferred from its actual operating current value and the ratio of the current transformers of the network, but must be determined experimentally. A simple method of doing this is described in Chapter VIII.

Summation Networks.—It is sometimes required in the design of protective systems, to obtain a resultant current the value of which shall be responsive to increases in any one, any pair, or all three of the lines of a three-phase system. Such a result obviously cannot be obtained by the equivalent of a simple vector summation of the line currents, as a resultant so obtained would for three-wire circuits be zero. The summation arrangements must combine unequal fractions of the line currents.

One method of obtaining a resultant current whose value is responsive to a change in any of the line currents is by means of the summation transformer illustrated graphically in Fig. 52. This transformer has three primary circuits carrying respectively the currents in A and C phases and the residual current.

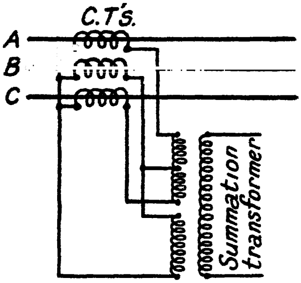
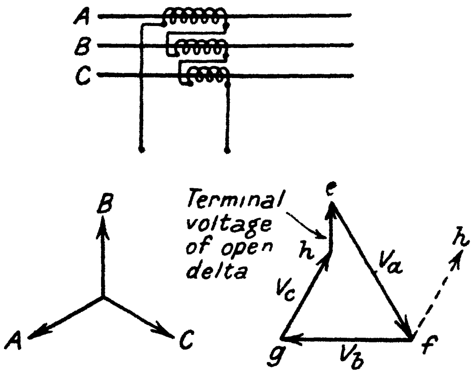


FIG 52.—SUMMATION TRANSFORMER

As the line currents circulate in opposite directions from the neutral conductor, the secondary current, with a balanced load will be proportional to $\sqrt{3}$ times the line current. A short-circuit between lines A and B, or B and C, will give a current in the summation transformer proportional to the current in the lines short-circuited. A short-circuit between lines A and C is reproduced in two of the windings of the summation transformer and the secondary current of this transformer will correspond to twice the short-circuit current. A residual current will flow in the third winding, and the effect of this winding will be assisted, unaffected, or opposed by the residual current in the other primary windings, according as the residual current is derived from lines A, B or C. The number of primary turns in the residual current winding is considerably greater than in the line current windings, so that the secondary current from the summation transformer is not greatly affected by the identity of the line from which the residual current is derived.

Another circuit giving a resultant current which is affected by changes in either of the line currents is shown in Fig. 53. The current transformers are here of the air gap type, have unequal ratios, and are connected in delta. The secondary voltages of the transformers will, due to the air gaps in the cores, be proportional to the line currents, and the resultant E.M.F. in the delta will, for a balanced load, be as shown in the vector diagram. The numbers of secondary turns in the three transformer cores are in the proportion of 6, 5 and 4.



Primary currents Secondary voltages

FIG. 53.—AN ARRANGEMENT OF CURRENT TRANSFORMERS GIVING A RESULTANT VOLTAGE DEPENDING UPON BOTH EARTH AND SHORT-CIRCUIT FAULTS

It will readily be seen from the vector diagram that, whereas for a balanced load in the main circuit, the resultant E.M.F. is represented by eh, this resultant for short-circuits between phases will be considerably greater, being represented by the distances eg, fh, or eh^1, this latter corresponding to a short-circuit between lines A and C, when there will be no E.M.F. induced in the secondary of B phase transformer. For earth fault currents, which flow in one line only, the resultant E.M.F. will be that induced in the corresponding transformer. It must be understood that the same current flows in all three secondary windings, there is no approximate balance of primary and secondary ampere turns such as occurs in an ordinary current transformer, and the total internal secondary impedance would be very high but for the fact that there are air gaps in the transformer cores.

Networks for Obtaining Artificial Voltages.—For pressures above 33 kV, voltage transformers are expensive, and are usually considered to constitute weak points in the system to which they are connected. For such high voltages it is therefore undesirable to avoid the use of voltage transformers for protective apparatus, as, on general grounds, it is irrational that apparatus for protection against the effects of faults

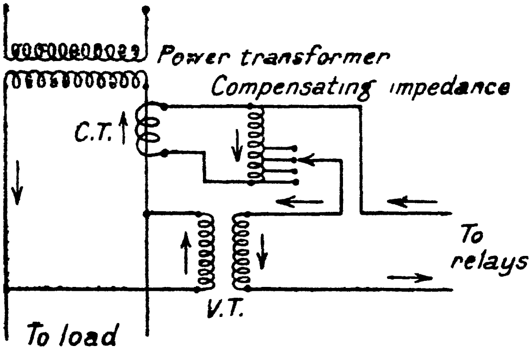


Fig 54.—A Circuit giving Compensation for the Impedance Drop in a Power Transformer

should increase the liability of such faults. A method of avoiding the use of voltage transformers on very high voltage networks which is becoming very usual is to make use of the secondary voltage of a power transformer for the operation of protective relays, the low voltage of the power transformer being still further reduced, if necessary, by means of a voltage transformer, which, operating as it will on a moderate primary voltage will be inexpensive and will introduce negligible risk of breakdown. Due to the high reactance drop in a power transformer, the secondary voltage of such a transformer will not be sufficiently representative of the secondary voltage for the operation of protective relays, and, accordingly, it is only possible to use this secondary voltage if a device is used to compensate for the impedance drop in the power transformer.

Fig. 54 is a schematic diagram showing the principle of the method of compensation as applied to a single-phase circuit. Here, it will be seen, there is connected in series with the primary burden of the voltage transformer a compensating impedance through which also flows the secondary current of a current transformer in the load circuit. The current in the compensating impedance is proportional to the current in the main transformer windings, and this impedance is so proportioned that the voltage drop on the impedance with the full load current is the same percentage of the nominal secondary voltage of the voltage transformer as the impedance drop of the power transformer, and that the phase angles of the two impedance drops are also the same. The voltage drop in the compensating impedance is seen to be added to the terminal voltage of the voltage transformer, and if the characteristics of this impedance are correct, the voltage impressed on the apparatus forming the burden of the voltage transformer will correspond to the primary voltage of the power transformer. It must be noted that the secondary current of the voltage transformer also flows in the compensating impedance, and this impedance, considered as part of the burden, will affect the ratio and phase error of the voltage applied to the relay coils. As a rule, however, the voltage transformer secondary current will be small as compared with that supplied from the current

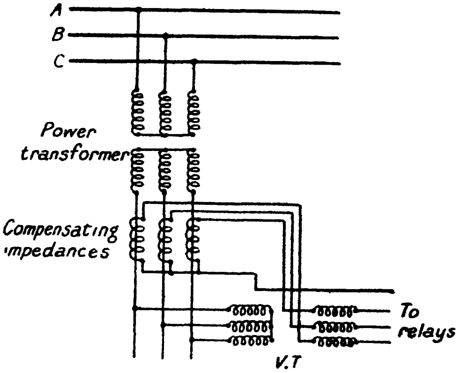


FIG. 55.—COMPENSATING IMPEDANCES FOR A STAR/STAR POWER TRANSFORMER.

transformer, and the effect of the compensating impedance, considered as part of the secondary circuit of the voltage transformer, will be negligible. The arrangement illustrated in Fig. 54 is intended for a power transformer with a tap changing feature, the magnitude of the compensating impedance being automatically varied by the tap changing gear to suit the ratio of the power transformer in use.

The arrangement shown in Fig. 54 can be simplified by designing the current transformer so that it serves as a compensating impedance. For this purpose the transformer will be of the air gap type, so that it gives a secondary voltage which bears the correct and constant ratio to the load current, and the secondary will be connected in series with the voltage transformer burden in such a way that the current transformer E.M.F. is added to the secondary voltage of the voltage transformer. This arrangement applied to a three-phase star/star power transformer is shown in Fig. 55, and, in the light of the foregoing explanation, will be readily understood.

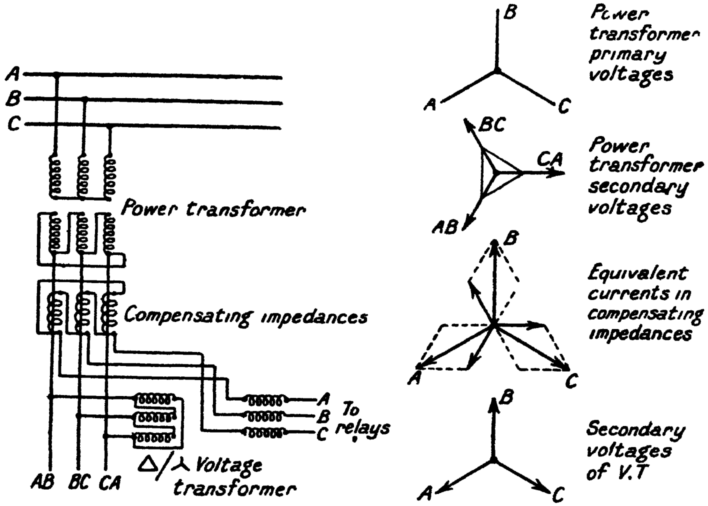

A
B
C
Power transformer
Compensating impedances
A
B
C
To relays
Δ/⅄ Voltage transformer
AB BC CA
B
A
C
Power transformer primary voltages
BC
CA
AB
Power transformer secondary voltages
B
A
C
Equivalent currents in compensating impedances
B
A
C
Secondary voltages of V.T

FIG 56.—COMPENSATING IMPEDANCES FOR A STAR DELTA POWER TRANSFORMER.

When the power transformer is of the star/delta type the method of compensation is not so simple if, as is usual, it is desired to connect the compensating impedances in the secondary or low-pressure mains, as the currents in these mains will be 30 degrees out of phase with the primary currents. One way of overcoming this difficulty is to connect the impedances in the secondary delta of the power transformer, but a preferable method is shown in Fig. 56, in which it will be seen that the compensating impedances are themselves connected in delta, while the voltage transformer is of the delta/star type. The delta connection of the impedances and of the primary of the voltage transformer negatives the 30-degree phase shift in the main power transformer so that both the secondary voltage system of the voltage transformer, and the compensating voltages derived from the impedances, correspond in phase to the primary voltage of the supply. The vector diagram shows the primary and secondary voltages of both transformers.

It must be noted that, notwithstanding the neutral of the high pressure side of the power transformer in either of the above schemes may be earthed, in neither case can a residual voltage be derived from the secondary system of the voltage transformer. In Fig. 55, although the power transformer is star star connected, it will invariably be of the core type, and we have already explained that this type is not competent for furnishing a residual voltage. In the scheme shown in Fig. 56, the delta connection of the secondary side of the power transformer eliminates the residual voltage completely, according to the principle discussed in connection with Fig. 27. It is possible to derive the equivalent of a residual voltage from a current transformer connected in the connection between the neutral of the high voltage side of the power transformer and earth. With this connection the direction of the residual current is compared with the constant direction of the current flowing from the transformer neutral to earth.

CHAPTER IV

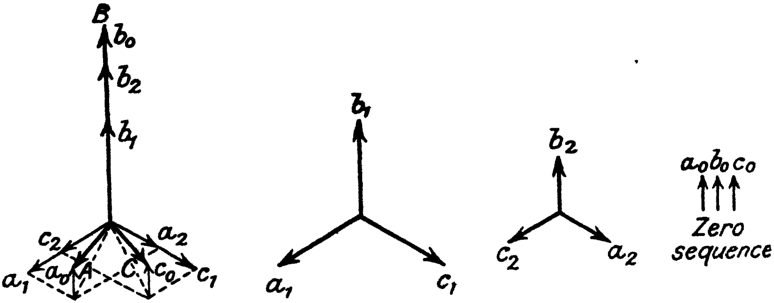
SYMMETRICAL COMPONENTS

Symmetrical Components.—We have now to consider a class of interconnection of protective transformers in which the current appearing in a particular part of the network depends upon the relation existing between the magnitudes of the three currents or voltages which define a three-phase system. We have already considered one such network, in its application both to current and voltage transformers, whereby what has been called the residual current or voltage in a three-phase system can be measured. A study of the other two classes of network of this kind depends upon a theory of three-phase circuits which was evolved in the United States by C. L. Fortescue. This theory has been of far-reaching importance, and its applications embrace not only the subject of automatic protection, but also that of the calculation of short-circuit and earth fault currents in transmission networks. In view of the importance of Fortescue's theory, and of the comparatively scanty literature relating to it in this country, we shall deal with the same in considerable detail.

If a three-phase circuit is three-wire, then, as the instantaneous sum of the line currents is at all times zero, the vectors of these currents form a closed triangle, and the magnitude of any two, and the phase difference between them being given, the magnitude and phase of the third current is fixed. If, due to an earth fault, the system becomes four-wire, this relation between the line currents no longer holds, and their three values and phases are independent. The phase voltages, between lines and neutral of a three-phase system likewise, for three-wire loading, form a closed triangle, but when the system carries an earth fault current, the three phase voltages become independent.

According to Fortescue, any system of three-phase currents *is the resultant of three component systems each of which is* symmetrical, *that is, the three currents of each of the three* symmetrical components are all equal. These three symmetrical components are respectively: a symmetrical three-phase system of normal or positive sequence, a second symmetrical three-phase system of a phase sequence opposite to normal known as a negative sequence component, and a third component of which the three line currents are all equal and in phase, this last being known as a zero phase sequence component.

We can illustrate this conception by starting with three symmetrical components as defined above, and by combining



Positive sequence. Negative sequence.

FIG. 57.—SYMMETRICAL COMPONENTS.

them into a resultant system. In Fig. 57 we have the vectors of these three components. The system of vectors a_1 b_1 and c_1 is the positive sequence component. It is symmetrical, and the phase sequence is normal in that the c_1 vector leads by 120 degrees on the a_1 vector. The system a_2 b_2 c_2 is the negative sequence system. This is also symmetrical, but the phase sequence is in the opposite sense to that of the positive sequence system, as the c_2 vector lags the a_2 vector by 120 degrees. The system a_0 b_0 c_0 is the zero sequence system. This system is also symmetrical in the sense that the three vectors are equal, but as these vectors are all in phase, the system cannot be said to have any phase sequence. It is therefore designated the zero sequence system. These three symmetrical components are compounded in such a way that the resultant A vector is the resultant of the a_1, a_2 and a_0

vectors of the three component systems, the resultant B and C vectors being obtained in like manner. The composition of the three symmetrical systems to obtain the resultant system A, B, C, is shown in the diagram.

In Fig. 57 the b vectors of all three components are in phase. The vectors of the several systems can bear any kind of phase relationship to each other, and it will readily be understood that by variation of the relative magnitudes and phase of the three systems a resultant system of any degree of dissymmetry can be built up. It will also be clear, from a study of Fig. 57, that if one set of corresponding vectors of the three systems are all in phase, the resultant system possesses one degree of symmetry.

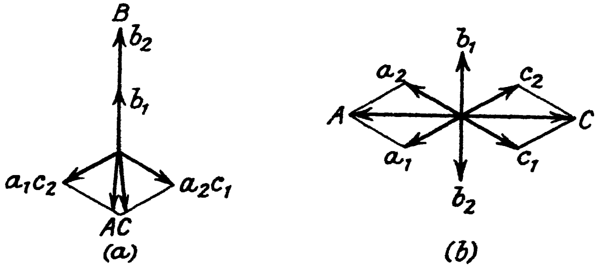


FIG 58.—EQUAL POSITIVE AND NEGATIVE SEQUENCE COMPONENTS GIVE A SINGLE-PHASE RESULTANT

Single-Phase Resultants of Symmetrical Components. —In Fig. 58 we have two cases in which the vectors of the positive and negative sequence components are equal. In one of these cases, corresponding vectors are in phase, in the other case they are in opposition. In each case the resultant of the positive and negative sequence systems is seen to be single-phase. In Fig. 58 (a) the resultant system is that which would be obtained by a non-inductive load supplied from line B and the mid point of an auto-transformer connected to lines A and C. In Fig. 58 (b) the resultant corresponds to a non-inductive single-phase load supplied from lines A and C. It can be proved by geometry, as we shall show hereafter that a positive and a negative sequence system of equal magnitude always combine to give a resultant single-phase system whatever be the phase relation of the two symmetrical components.

If we add to the system shown in Fig. 58 (a) a zero sequence system whose magnitude is equal to that of the positive and negative sequence systems, and which is in phase with the b vectors of these systems, the A and C resultants are zero, and the B resultant is three times the magnitude of either of the three components, as shown in Fig. 59. This resultant evidently corresponds to what has been called a residual current or voltage, and it is thus seen that the magnitude of the residual is equal to three times that of the zero sequence component. It is also seen that an earth fault current, flowing in one line only, can, according to the theory of Fortescue, be considered as the resultant of equal positive, negative and zero sequence components.

It appears from the above elementary considerations that a balanced system of three-phase currents and voltages comprises a positive sequence component only, the negative and zero sequence components being zero. The appearance of a negative sequence component results in an unsymmetrical system of currents and voltages, the vectors of which still form a closed triangle. An unbalanced three-wire system thus comprises a positive and a negative sequence component, but no zero sequence component. When the three-phase system becomes four-wire a zero sequence component appears, and the magnitude of this component is one-third that of the residual of the system. The currents of a single-phase load drawn from a three-wire three-phase system comprise equal positive and negative sequence components.

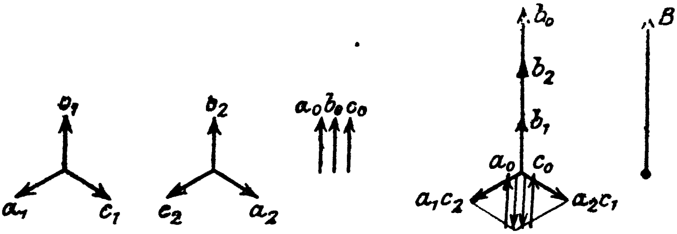


FIG 59—AN EARTH FAULT CURRENT RESOLVED INTO EQUAL POSITIVE, NEGATIVE AND ZERO SEQUENCE COMPONENTS

It should be obvious that the magnitude of the negative sequence component cannot exceed that of the positive sequence component. If the negative sequence component were the greater, the phase sequence of the resultant system would be reversed.

The Resolution of Unsymmetrical Three-Phase Systems.—The resolution of unsymmetrical three-phase systems into their symmetrical components is a problem of great practical importance, since the presence of a negative or a zero sequence component is indicative of an abnormal condition of the circuit in which these components of the currents or voltages are found. It appears from basic principles that as both positive and negative sequence components are three-phase and symmetrical, if the three currents or phase voltages of an unsymmetrical three-phase are compounded, the positive and negative sequence components will disappear, and the resultant will consist solely of the three zero sequence currents or voltages. We have already considered this compounding of the three currents of a three-phase system in connection with the circuit shown in Fig. 25. The residual current in this circuit consists of the three line currents of the zero sequence system. We have also seen that when three current transformers in a three-phase circuit are delta connected, the resultant currents contain no residual. These resultant currents are each the differences of two line currents, and as in any pair of line currents the zero sequence currents are equal and in phase, it is manifest that these currents will disappear from the resultant difference of the two line currents.

As the introduction of a negative sequence component into a three-phase system gives an unbalanced resultant, so dissymmetry is indicative of a negative sequence component. Although single-phase loads are taken from supply networks by domestic consumers, and also by industrial welding equipments, the diversity of such single-phase loads, and their relatively small magnitude as compared with the balanced loads, results in the line currents of large transmission systems being very approximately balanced. We may remark at this stage that, although single-phase loads supplied between lines neutral of a three-phase four-wire distribution system, give a residual in this system, these residual currents appear as single-phase loads between lines in the high-pressure three-wire system supplying the step-down transformers. The presence of a considerable negative sequence component of the currents or voltages of a transmission line is an almost certain indication of a short-circuit fault. On large and extensive systems, short-circuits between lines do not necessarily give rise to excessive currents, and a method of detecting short-circuits other than by the measurement of the magnitude of the line currents is of considerable practical importance. The resolution of the system of line currents or voltages to separate out the negative sequence component is a solution of this problem.

The basis of the most convenient method of resolution can be easily understood without the aid of mathematical reasoning.

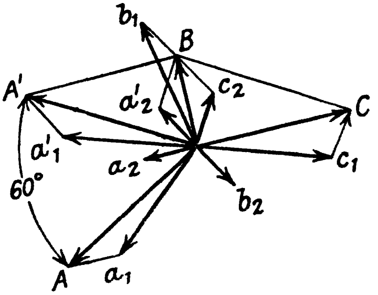


FIG 60 —THE RESOLUTION OF AN UNSYMMETRICAL THREE-PHASE SYSTEM.

Let us assume we have two resultant currents derived from the system to be resolved, and from which the zero sequence component has been eliminated. These two currents are each the resultant of a positive and negative sequence component, and the phase difference between the two positive sequence and the two negative sequence components is 120 degrees. If now, by artificial means, the phase of the leading current is retarded by 60 degrees, so that the actual phase difference between the currents is reduced by 60 degrees, then the phase difference between the positive sequence components will be reduced by a like amount. A lag of the positive sequence component will, however, correspond to a lead of the corresponding negative sequence component, and the effect of the artificial phase shift is to increase the phase separation of the negative sequence components to 180 degrees, so that they cancel. The resultant of the two currents, with their phase separation reduced by 60 degrees, thus contains the positive sequence component only, and the magnitude of this resultant is $\sqrt{3}$ times that of the positive sequence component. Reasoning in like manner we find that if the phase of the lagging current is retarded by 60 degrees the positive sequence components are brought into phase opposition and disappear, while the resultant contains the negative sequence component only.

The foregoing argument is illustrated by the vector diagram, Fig. 60. Here the unbalanced system A, B, C, is compounded of the positive sequence system a_1 b_1 c_1 and the negative sequence system a_2 b_2 c_2. The vector A is retarded in phase by 60 degrees to assume the position A^1, and its positive and negative sequence components become a_1^1 and a_2^1. It is readily seen that a_1^1 is now in phase opposition to c_1, and that the resultant of A^1 and C is the same as the resultant of a_2^1 and c_2, and, as a_2^1 and c_2 are 60 degrees apart in phase, this resultant is $\sqrt{3}$ times that of the negative sequence component. The phase of this resultant is seen to be 30 degrees displaced from that of c_2.

Vector Analysis of Three-Phase Circuits.—The resolution of unsymmetrical three-phase circuits can be studied much more conveniently by vector analysis than by geometrical methods. Such analysis is much simplified by the use of a unit vector operator h, which imparts rotation through 120 degrees. This unit vector is symbolically represented by $\frac{1}{2}(-1+\sqrt{3}j)$, or $e^{\frac{2\pi j}{3}}$; h^3 is therefore equal to unity. Since multiplication by h causes rotation through 120°, multiplication by h^2 will, by the usual conventions, cause rotation through 240°. A symmetrical system of unit three-phase vectors is thus expressed symbolically as

$$1 + h + h^2 = 0,$$

since the resultant of such a system is zero.

The values of various powers of the h operator are shown in Fig. 61. By recollecting the basic convention that the angular displacement is represented by the index of h, this diagram will be readily understood.

The following relations will be required in the analysis of the resolution of three-phase circuits:

Since $1 + h + h^2 = 0$

$1 + 2h + h^2 = (1 + h)^2 = h$

thus $1 + h = h^{\frac{1}{2}} = -h^2$

also $1 + h^2 = -h = h^{\;\frac{1}{2}}$.

and $(1 - h)^2 = 1 + h^2 - 2h = -3h = 3h^{-\frac{1}{2}}$

whence $1 - h = 1 + h^{-\frac{1}{2}} = \sqrt{3}\,h^{-\frac{1}{4}}$

similarly $1 - h^2 = 1 + h^{\frac{1}{2}} = \sqrt{3}\,h^{\frac{1}{4}}$.

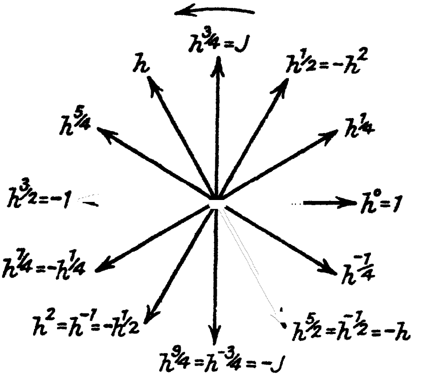


FIG 61 —THE h OPERATOR

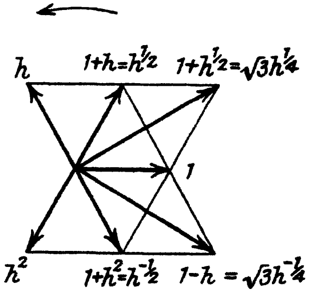


FIG 62 —FUNCTIONS OF THE h OPERATOR

These relations are illustrated in Fig. 62, and their geometrical derivation will be readily perceived.

Consider now a three-phase system of vectors, A, B and C, in which the phase of the A vector is in advance of that of the B vector. Each of these vectors is the resultant of a positive sequence, a negative sequence and a zero sequence component. If the magnitude of the positive sequence vectors be p, then this system can be represented symbolically as

$$p, \; hp, \text{ and } h^2p,$$

corresponding respectively to the resultant vectors B, A and C. The positive sequence component of A is, as shown by the h operator, 120 degrees in advance of the corresponding component of B. The positive sequence component of C is 240 degrees in advance of that of B, this being indicated by the operator h^2. The negative sequence vectors will be, respectively,

$$q,\ h^2q,\ \text{and}\ hq,$$

q being their magnitude. The negative sequence component of A lags that of B by 120 degrees, as indicated by the h^2 operator. The zero sequence components, being equal and in phase, can be represented by

$$r,\ r,\ \text{and}\ r.$$

The three resultant vectors can thus be symbolically represented:

$$B = p + q + r$$
$$A = hp + h^2q + r$$
$$C = h^2p + hq + r.$$

From these equations we see at once that

$$A + B + C = 3r,$$

since the resultant operator for both p and q in the sum is $1 + h + h^2 = 0$.

The resultant of the three vectors A, B and C is thus equal to three times the zero sequence current.

If we advance the A vector 240 degrees, which is represented symbolically by multiplying by h^2, and advance the C vector by 120 degrees, represented by multiplication by h, we obtain

$$B = p + q + r$$
$$h^2A = h^3p + h^4q + h^2r$$
$$hC = h^3p + h^2q + hr.$$

Remembering that $h^4 = h$, and that $h^3 = 1$, we see that

$$B + h^2A + hC = 3p,$$

the effect of the transformation being to convert the zero sequence vectors into a three-phase system, and to reverse the sequence of the negative sequence vectors.

Similarly $$B + hA + h^2C = 3q.$$

Further $$B - A = (1 - h)\,p + (1 - h^2)q$$
$$= \sqrt{3}\,\{h^{-\frac{1}{4}}p + h^{\frac{1}{4}}q\}$$
$$= \sqrt{3}h^{-\frac{1}{4}}\,(p + h^{\frac{1}{2}}q).$$

Similarly $A - C = (h - h^2)p + (h^2 - h)q$

$$= \sqrt{3}(h,h^{-\frac{1}{2}}p + h^2,h^{\frac{1}{2}}q) \quad \textit{since} \quad h = h^4$$

$$= \sqrt{3}h^{-\frac{1}{2}}(hp + h^2h^{\frac{1}{2}}q)$$

and $C - B = \sqrt{3}h^{\frac{1}{2}}(h^2p + hq) = \sqrt{3}h^{-\frac{1}{2}}(h^2p + hh^{\frac{1}{2}}q)$.

These operations give the vector differences of the three pairs of a three-phase system of vectors, such as are obtained by the delta connection of three current or voltage transformers. The effect of the delta connections is thus to eliminate the zero sequence component, and to give a system in which the magnitudes of both positive and negative sequence components are $\sqrt{3}$ times the corresponding components of the original system.

Let us now consider the system

$$B = p + q$$
$$A = hp + h^2q$$
$$C = h^2p + hq,$$

in which there is no zero sequence component, and represent symbolically the method of resolution already dealt with on p. 91. By this method we obtain the positive sequence component by retarding the phase of the A vector by 60 degrees, and compounding this vector, so modified, with the B vector. Since retardation in phase by 60 degrees is represented by multiplication by $h^{-\frac{1}{2}}$, the resultant will be

$$B + h^{-\frac{1}{2}}A$$
$$= p + q + h^{\frac{1}{2}}p + h^{\frac{3}{2}}q$$
$$= p(1 + h^{\frac{1}{2}}) + q(1 + h^{\frac{3}{2}})$$

Since, from Fig. 62, $h^{\frac{3}{2}} = -1$, we have

$$B + h^{\frac{1}{2}}A = \sqrt{3}h^{\frac{1}{2}}p.$$

The resultant is thus equal to $\sqrt{3}$ times the positive sequence component, and leads this component of the B vector by 30 degrees.

By retarding the phase of the C vector by 60 degrees we obtain

$$B + h^{-\frac{1}{2}}C$$
$$= p + q + h^{\frac{3}{2}}p + h^{\frac{1}{2}}q$$
$$= \sqrt{3}h^{\frac{1}{2}}q.$$

This resultant is $\sqrt{3}$ times the negative sequence component, and leads this component of the B vector by 30 degrees.

This analysis confirms the geometrical reasoning illustrated by Fig. 60.

Before proceeding to deal with the practical applications of the results obtained above we give a short geometrical investigation which throws further light upon the nature of symmetrical components.

At Fig. 63 (a) we have a system of three-phase vectors without a residue, which can be translated into the closed triangle EFG at (b). If we describe equilateral triangles, FGL and FGM, on each side of GF, the vectors EL and EM are respectively the resultants obtained by compounding B with A retarded and advanced in phase by 60 degrees. EL and EM are therefore respectively equal to $\sqrt{3}$ times the positive sequence and $\sqrt{3}$ times the negative sequence components of the A, B, C system. By geometry,

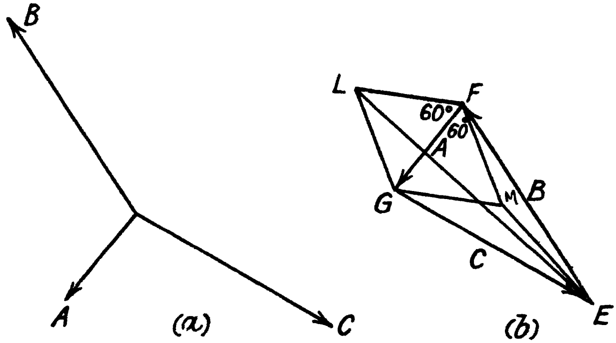


FIG. 63 —ILLUSTRATING A GEOMETRICAL PROPERTY OF SYMMETRICAL COMPONENTS

$$EL^2 = 3p^2 = A^2 + B^2 - 2AB \cos (EFG + 60^\circ)$$

$$= A^2 + B^2 - AB \cos EFG + \sqrt{3}AB \sin EFG$$

$$\cos EFG = \frac{A^2 + B^2 - C^2}{2AB}$$

and AB sin EFG = 2S, the area of the triangle EFG.

Thus $\qquad 3p^2 = \frac{1}{2}(A^2 + B^2 + C^2) + 2\sqrt{3}\, S.$

Similarly $\quad 3q^2 = EM^2 = \frac{1}{2}(A^2 + B^2 + C^2) - 2\sqrt{3}\, S.$

These expressions for p and q are symmetrical functions of A, B and C. The magnitude of p and q so determined does *not therefore depend upon the pair of vectors which have been compounded.*

Further, $$3\,(p^2+q^2)=\Sigma A^2.$$

The sum of the squares of the positive and negative sequence components is thus equal to one-third of the sum of the squares of the magnitudes of original vectors, and is independent of their phase relationship. We have here a mathematical analogy between the symmetrical components of a system of three-phase currents or voltages and the active and reactive components of an alternating current. When an unbalanced system of currents is associated with a symmetrical voltage system this analogy is even more striking, as the negative sequence component can carry no power, while the positive sequence system combined with the symmetrical voltage system gives what is known as the total equivalent volt-amperes of the circuit.

Finally, when the area of the triangle EFG becomes zero, the system A, B, and C becomes single-phase, and,

$$3p^2=3q^2=\tfrac{1}{2}\Sigma A^2.$$

The positive and negative sequence components are now equal. This result, it may be noted, does not depend upon any assumption regarding the phase relationships of A, B, C, *p* or q.

Direct Measurement of the Symmetrical Components of Unbalanced Three-Phase Systems.—We have already described, in a previous chapter, methods of interconnecting current and voltage transformers to give the zero sequence component of an unbalanced three-phase system. For the sake of completeness we reproduce the connections for these circuits in Fig. 64, (a) showing the network for the zero sequence current, and (b) that for the zero sequence voltage.

In Fig. 65 we have a network for resolving a three-phase voltage system. The voltage transformers being delta connected on the primary side, the secondary voltages will, as we have seen, contain no zero sequence component. The secondary windings of the transformers are connected in star, and two impedances are connected as shown. The ohmic values of these impedances are equal, but the phase angle of the one connected to the lagging voltage is 60 degrees greater than that of the impedance connected to the leading voltage. The currents in these impedances will be proportional to the two line voltages, but the phase difference between them will be 60 degrees greater than the phase difference between the voltages. It therefore follows that, provided the impedance of the common return lead for the circuit is negligible, the current in this circuit will be proportional to the negative sequence component of the voltage system. If the two impedances be interchanged, so that the more inductive one is connected to the leading phase, then the current in the common lead will be proportional to the positive sequence component of the voltage system.

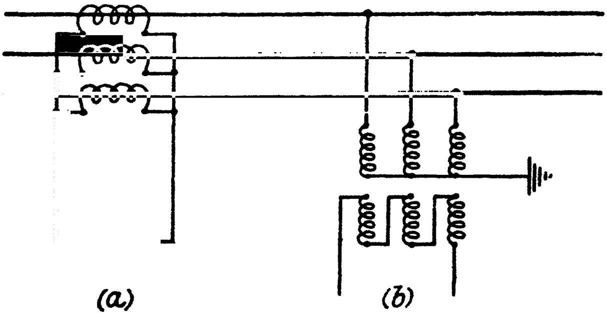

(a) (b)

FIG. 64.—NETWORKS FOR ZERO SEQUENCE CURRENTS AND VOLTAGES

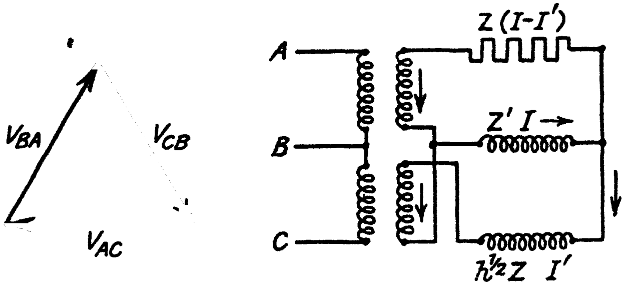


FIG. 65.—A NETWORK FOR MEASURING THE NEGATIVE SEQUENCE VOLTAGE.

If the impedance on the common return lead has a value Z^1, then, calling the two impedances directly connected to the transformer secondaries Z and $h^{\frac{1}{2}}Z$, and marking in on the circuit diagram the value of the currents, I, I^1, and $I - I^1$, we have

$$V_{BA} = Z\,(I - I^1) + Z^1 I$$

$$V_{CB} = h^{\frac{1}{2}} Z I^1 + Z^1 I.$$

We have seen that if q be the negative sequence component

$$V_{BA} + h^{-\frac{1}{2}} V_{CB} = \sqrt{3}h^{\frac{1}{2}}q,$$

thus:

$$V_{BA} + h^{-\frac{1}{2}} V_{CB} = ZI - ZI^1 + Z^1 I + ZI^1 + h^{-\frac{1}{2}} Z^1 I = \sqrt{3}h^{\frac{1}{2}}q$$

$$= I\,\{Z + (1 + h^{-\frac{1}{2}} Z^1)\}\,,$$

and $$I = \frac{\sqrt{3}h^{\frac{1}{2}}q,}{Z + \sqrt{3}h^{-\frac{1}{2}} Z^1}.$$

The denominator of this fraction is a constant of the network. Thus I is proportional to the negative sequence component of the voltage whatever the value of Z^1 may be. The phase of I will be modified by the impedance in the common return lead, but for a given network the magnitude and phase of I depend only upon the negative sequence component of the voltage system. If the impedance with the greater phase angle is connected to the transformer giving the leading voltage V_{BA}, then we shall have

$$V_{BA} = h^{\frac{1}{2}} Z\,(I - I^1) + Z^1 I$$

and $$V_{CB} = ZI^1 + Z^1 I.$$

The positive sequence component of the voltage is proportional to

$$h^{-\frac{1}{2}} V_{BA} + V_{CB} = ZI - ZI^1 + h^{-\frac{1}{2}} Z^1 I + ZI^1 + Z^1 I$$

$$= I\,(Z + \sqrt{3}h^{-\frac{1}{2}} Z^1).$$

The effect of the impedance Z^1 on the value of I obtained in a positive sequence network can be illustrated by a numerical example. Let the impedances connected to the transformer secondaries be each equal to 50 ohms, the one being non-inductive and the other inductive with a phase angle of 60 degrees. Let the impedance in the common return be one of

10 ohms, perfectly inductive. Then if the resultant voltage $h^{-\frac{1}{4}}V_{BA} + V_{CB}$ be called V,

$$I = \frac{V}{50 + \sqrt{3}h^{-\frac{1}{4}}.j.10}.$$

As
$$h^{-\frac{1}{4}} = \frac{\sqrt{3}}{2} - \frac{1}{2},$$

the denominator of this fraction becomes

$$50 + \sqrt{3}j\left(\frac{\sqrt{3}}{2} - \frac{j}{2}\right) \times 10$$
$$= 58{\cdot}7 + 15j.$$

The value of the current I will therefore be $\frac{V}{60{\cdot}5}$ instead of $\frac{V}{50}$, the value had Z^1 been zero. The effect of Z^1 will also include a phase shift of I equal to arc tan $\frac{15}{58{\cdot}7}$ = 14 degrees approx.

We have seen that the positive sequence component is given by:

$$h^{-\frac{1}{4}}V_{BA} + V_{CB} = I\,(Z + \sqrt{3}h^{-\frac{1}{4}}Z^1).$$

Assuming that the impedance Z is non-inductive, then the impedance Z^1 will cause no phase shift of I, if the quantity $h^{-\frac{1}{4}}Z^1$ is real. The phase of Z^1 must be expressed by the operator $h^{\frac{1}{4}}$, for this condition to be satisfied. The impedance Z^1 must thus be inductive, with a phase angle of 30 degrees, if its presence in the network is to affect only the magnitude, and not the phase of I.

In Fig. 66 we have an arrangement for obtaining the complete three-phase negative sequence component of a voltage system. T_1, T_2, and T_3 are the secondary windings of a three-phase voltage transformer. R_1 and Z_1 are impedances of equal ohmic value, the phase angle of Z_1 being 60 degrees greater than that of R_1. R_2Z_2 and R_3Z_3 are other pairs of impedances equal in ohmic value to R_1 and Z_1, and with similar respective phase angles. The members g_1, g_2 and g_3 of the network carry equal currents, which are proportional in magnitude to the negative sequence component of the three-phase voltage, and which mutually differ in phase by 120 degrees.

Fig. 67 shows a network for obtaining the symmetrical components of an unbalanced system of currents. Two current transformers are used in each of two lines, each pair being so connected as to give the vector difference of two line currents. These resultant currents, as we have seen, contain no zero phase sequence component. Two impedances Z, of equal ohmic value, are connected as shown, the phase angles of these impedances differing by 60 degrees. Z^1 is the circuit carrying the current proportional to the symmetrical component measured. Denoting, as before, the inductive impedance by $h^{\frac{1}{2}}Z$, then, the distribution of currents in the network

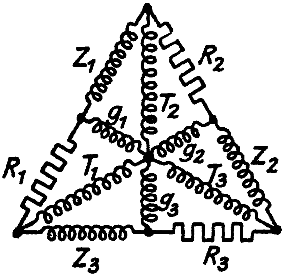


Fig 66 —A Network giving the Complete Three-Phase System of Negative Sequence Voltages

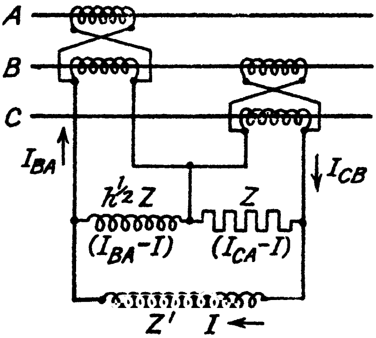


Fig 67 —A Network for Measuring Negative Sequence Currents

being as marked on the diagram, we have, equating the volt drop in the two impedances Z to that in Z^1,

$$IZ^1 = h^{\frac{1}{2}}Z\,(I_{BA} - I) + Z\,(I_{CB} - I)$$

and
$$I = (h^{\frac{1}{2}}I_{BA} + I_{CB})\,\frac{Z}{Z^1 + \sqrt{3}h^{\frac{1}{2}}Z}.$$

As I_{BA} is the leading current, the quantity $(h^{\frac{1}{2}}I_{BA} + I_{CB})$ represents the resultant of the two currents with their phase separation increased by 60 degrees. The quantity $Z/(Z^1 + \sqrt{3}h^{\frac{1}{2}}Z)$ is a network constant. The current I in the branch Z^1 is therefore proportional to the negative sequence component of the line currents.

It will readily be understood that if the more inductive impedance be connected to the transformers giving the current I_{CB} the current in the branch Z^1 will be proportional to the positive sequence component.

The principle of the network in Fig. 67 can be understood without the aid of mathematical analysis. The current from the transformers in lines B and A divides into two portions, the one flowing directly through the impedance Z directly connected to it, and the other through the branch Z^1 and the impedance connected to the other pair of transformers. As the impedance is connected to the B and A transformers, the component in Z^1 will lead the total current I_{BA}. Similarly the component of the I_{CB} current in Z^1 will lag the total current. The phase difference of the component currents in Z^1 is thus 60 degrees greater than that of the currents I_{BA} and I_{CB}. Reasoning on similar lines we find that when the network is arranged to give the positive sequence component in Z^1, the portions of the main secondary currents in Z^1 have a phase difference 60 degrees less than I_{BA} and I_{CB}.

By reasoning similar to that used in the investigation of networks for symmetrical components of voltage systems we can show that, in order that the impedance Z^1 shall not affect the phase of the current I, this impedance must have a phase angle of 30 degrees, and the current in it must lead the voltage.

Symmetrical Components of Two-Phase Systems.—For some purposes it is convenient to convert a three-phase system into a two-phase system for the purpose of resolution into symmetrical components The reason for this procedure is that, as we shall see hereafter, the phase angle differences of the impedances in the resolving networks is 90 degrees for a two-phase circuit, and this phase difference is more convenient to obtain than that of 60 degrees requisite in a three-phase network. We shall investigate the relation between the symmetrical components of a derived two-phase system and those of the original three-phase system.

Fig. 68 (a) is the vector diagram for a two-phase voltage system derived from a three-phase system by Scott-connected voltage transformers.

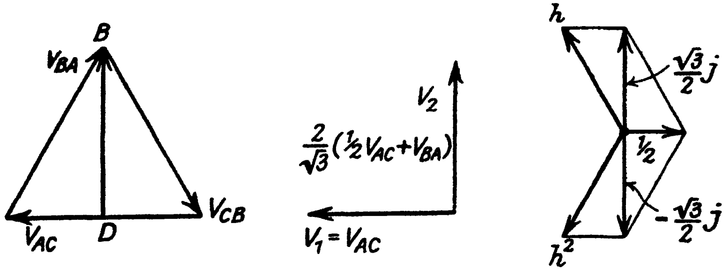
The vectors of the two-phase voltages are V_1 and V_2. V_1 is equal to V_{AC}, and V_2 is $\frac{2}{\sqrt{3}}$ times $(\frac{1}{2}V_{AC} + V_{BA})$. As the three-phase system of line voltages contains no zero sequence component we may put

$$V_{AC} = p + q$$
$$V_{BA} = h^2p + hq$$

since V_{BA} lags V_{AC} by 120 degrees,

thus
$$V_1 = p + q$$

and
$$V_2 = \frac{2}{\sqrt{3}}(\tfrac{1}{2}V_{AC} + V_{BA})$$
$$= \frac{2}{\sqrt{3}}\{(h^2 + \tfrac{1}{2})p + (h + \tfrac{1}{2})q\}.$$



(a) (b)

FIG. 68.—THE CONVERSION OF A THREE-PHASE TO A TWO-PHASE SYSTEM

From Fig. 68 (b) we see that

$$h^2 + \tfrac{1}{2} = -\frac{\sqrt{3}}{2}j, \text{ and } h + \tfrac{1}{2} = \frac{\sqrt{3}}{2}j.$$

Thus
$$V_2 = -jp + jq$$
$$V_1 = p + q.$$

From these equations we find that

$$V_1 + jV_2 = 2p \text{ and } V - jV_2 = 2q.$$

The resolution of the two-phase system thus gives the positive and negative sequence components of the three-phase system from which it is derived.

The measurement of the symmetrical components of the two-phase voltage system is carried out by the use of the network shown in Fig. 69. Z is a non-inductive resistance, and $-jZ$ is a capacitance of equal ohmic value to Z. The following relations are read off from the diagram :

$$V_1 = ZI - ZI^1 + Z^1I$$
$$V_2 = -jZI^1 + IZ^1$$
$$jV_2 = ZI^1 + jIZ^1$$

and
$$V_1 + jV_2 = I\{Z + (j + 1)Z^1\} .$$

As $\{Z + (j + 1) Z^1\}$ is a network constant, I is proportional to the positive sequence component. If the positions of the non-inductive resistance and the capacitance be interchanged, the current in Z^1 will evidently be proportional to the negative sequence component.

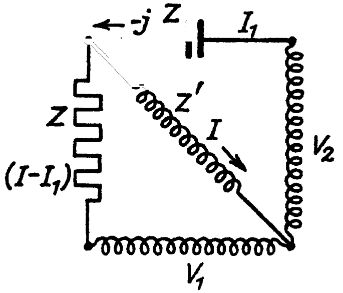
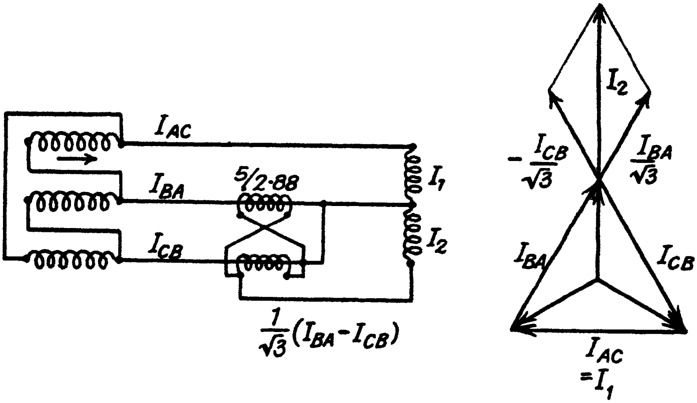


Fig 69 —The Resolution of a Two-Phase Voltage System

Since in the above result, Z represents the vector of a non-inductive impedance, with zero phase angle, the impedance Z^1 will cause no phase shift of I if its phase angle be equal and opposite to $(j + 1)$. The vector $(j + 1)$ attached to an impedance indicates that the current in it lags the voltage by 45 degrees. In order that the quantity $(j + 1) Z^1$ be real, Z^1 must have a phase angle of 45 degrees, the current in it leading the voltage.

The symmetrical components of a system of three-phase currents cannot be obtained by the resolution of the two-phase system obtained from the circuit shown in Fig. 68. An examination of this diagram shows that one current of the two-phase system is identical with one of the secondary line currents of the three-phase system. This current will thus contain any zero sequence component in the system. The second current of the two-phase system is proportional to the difference of two line currents on the three-phase side, and this difference current can contain no zero sequence component. The two-phase system must be derived from a three-phase system from which the zero sequence component has been eliminated. Fig. 70 shows a network for effecting the required transformation. Three current transformers, delta connected, give a three-phase system without a residue. One current of this system is one of the currents of the two-phase system. The second current of the two-phase system is obtained by compounding the remaining currents of the three-phase system in the manner shown, by using two current transformers each having a ratio of 5/2·88. The two-phase currents given by this network will evidently be in phase with the two-phase voltages represented in Fig. 68 when the three-phase system is balanced, and its power factor unity.



I_{AC}
I_{BA}
I_{CB}
5/2·88
I_1
I_2
$\frac{1}{\sqrt{3}}(I_{BA}-I_{CB})$
I_2
$-\frac{I_{CB}}{\sqrt{3}}$
$\frac{I_{BA}}{\sqrt{3}}$
I_{BA}
I_{CB}
I_{AC}
$=I_1$

FIG 70.—ELIMINATING THE ZERO SEQUENCE COMPONENT FROM A THREE-PHASE SYSTEM AND CONVERTING TO A TWO-PHASE SYSTEM.

The resolution of a system of three-phase currents by conversion to two-phase does not present the same advantages as apply to the resolution of a voltage system. The impedances in the resolving network must have a phase angle difference of 90 degrees for both currents and voltages, and this phase difference is not conveniently obtainable in impedances of the relatively low value which must be used in a network for current resolution.

The Association of Symmetrical Components of Currents and Voltages.—In the general case of an unbalanced three-phase system, both currents and voltages will contain positive, negative and zero sequence components. We may take it as practically axiomatic that the association of a current of one phase sequence with a voltage of a different phase sequence will give rise to no average power. We have thus only to consider the association of symmetrical components of currents and voltage having the same phase sequence, and the relative directions of these components are of importance in the technique of automatic protection.

The association of positive sequence currents and voltages calls for little comment. In normal circuits, the negative sequence voltages are negligibly small, and the relative directions of the positive sequence currents and voltages are considered to be such that their association gives a direction corresponding to the flow of power in the circuit.

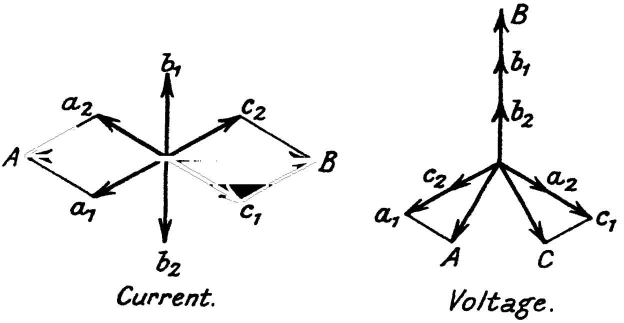


FIG. 71 —ILLUSTRATING POSITIVE AND NEGATIVE SEQUENCE POWER

The association of negative sequence currents and voltages is not so simple. A negative sequence component in a system of three-phase currents gives rise to an unbalanced voltage system. The unbalancing of the voltages is, however, of a different character from that of the currents. This point is illustrated in Fig. 71. Here we have represented a single-phase current carried by lines A and C which is shown resolved into equal positive and negative sequence components. This current will produce an unbalancing of the voltage system of the kind shown in the diagram. The phase voltages are also *shown resolved into their positive and negative sequence components, and, for the sake of simplicity, the positive sequence* component is shown as double the negative sequence component. It will be seen at once that positive sequence currents and voltages are in phase, while negative sequence currents and voltages are in opposition. If we consider that the association of symmetrical components of current and voltage gives rise to positive and negative sequence power, it appears that, for the conditions represented in Fig. 71, the negative sequence power flows in the opposite direction to the positive sequence power. The positive sequence power, flowing towards the single-phase load, is twice the actual power, and this difference is brought about by a flow of negative sequence power from the load to the supply.

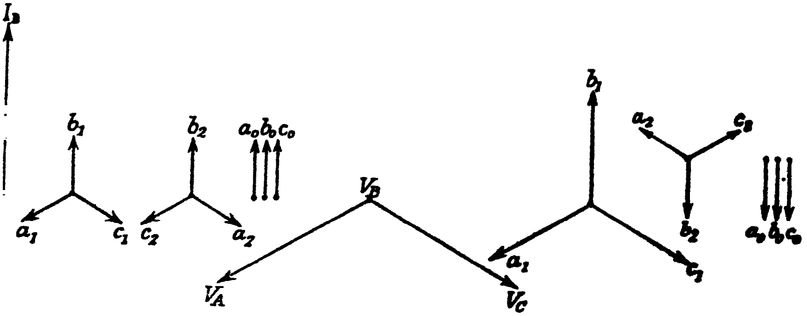


FIG. 72.—SHOWING THE POSITIVE, NEGATIVE AND ZERO SEQUENCE POWER IN AN EARTH FAULT.

The association of zero sequence currents and voltages can be considered by a study of the conditions represented in Fig. 72, which correspond to an earth fault current supplied from a star-connected generator with an earthed neutral point, the voltage of the earthed phase being presumed to have practically disappeared. The single current in the earthed line is, as we have shown, the resultant of equal positive, negative and zero sequence components. The resolution of the voltage system represented by the two phase voltages V_A and V_0 gives also equal negative and zero sequence components. The positive sequence components of the currents and voltages are seen to be in the same direction. The directions of the negative and zero sequence components are opposed. We conclude, therefore, that the direction of both negative and zero sequence power in an earth fault is opposite to that of the positive sequence power.

Although currents proportional respectively to positive sequence currents and voltages can be obtained by means of the networks shown in Figs. 65 and 66, it must not be assumed that such currents can be associated in a wattmeter to give positive sequence power. In Fig. 73 we have drawn the vector diagram for the networks when connected in a balanced circuit in which the power factor is unity. The current in the voltage network is the resultant of two equal currents, the one in phase with the lagging voltage V_{BA} and the other lagging 60 degrees on the leading voltage V_{AC}. This resultant is shown as $I_p{}^1$. The resultant current representing the positive sequence current is obtained by splitting each of two line currents into components with a 60-degree phase difference. The lagging component of the leading phase current I_{AC} and the leading component of the lagging phase current I_{BA} are combined to give the resultant I_p, which is proportional to the positive sequence current. It is at once seen that $I_p{}^1$ lags I_p in phase by 30 degrees, whereas the actual positive sequence current and voltage are in phase. The vector diagram illustrates conditions in which the impedance of the branches carrying the resultant currents is negligible. We have seen, however, that the effect of impedances in these branches is to modify the phase of the resultant currents. A

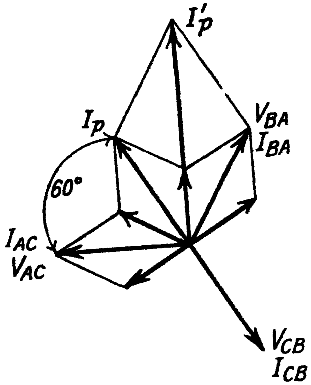


FIG 73.—ASSOCIATION OF CURRENTS AND VOLTAGES DERIVED FROM POSITIVE SEQUENCE NETWORKS

reference to the equation on p. 98 will show that if the impedance of the branch carrying the resultant current has a phase angle corresponding to $h^{\frac{1}{4}}$, so that the current in it lags the voltage by 30 degrees, this impedance will produce a 30° lag of the current representing the positive sequence components, so that the two resultants for positive sequence current and voltage will be in phase for a positive sequence power factor of unity.

The Utility of the Theory of Symmetrical Components.—At first consideration the theory of symmetrical components may appear to introduce unnecessary complication into the study of unbalanced three-phase currents and voltages. A single-phase earth fault current is, according to this theory, to be replaced by no less than nine components, two sets of three cancelling and leaving no resultant. A single-phase current supplied by two lines is likewise replaced by six components, two of which cancel and leave no resultant. Single-phase currents flowing alone in a three-phase circuit, however, represent limiting currents. The general case of an unbalanced system of three-phase currents comprises three currents, and can only be completely specified either by the magnitude of the three currents or the magnitude of two currents and their phase difference. Although, according to the theory of symmetrical components, these three unbalanced currents are replaced by six components, the system, in terms of these symmetrical components, is completely specified by two magnitudes and a phase difference, since a symmetrical system is completely defined by one of its members. The complication introduced by the symmetrical component conception is thus only apparent. Similarly, if a three-wire three-phase system becomes four-wire due to the incidence of an earth fault, the three line currents are completely independent, and the system can only be completely defined by three magnitudes and two phase angles. The alternative definition in terms of symmetrical components also involves three magnitudes and two phase angles, so that, in this case also, no real complication is introduced.

The utility of the symmetrical component theory can be realised by a study of the flow of earth fault currents in a system comprising static transformers, of the star/delta type, with the neutrals earthed. An elementary case of such a system is shown in Fig. 74, which represents a delta-wound generator feeding a line to which is connected a star/delta transformer with earthed neutral. The flow of current in the system with an earth fault on B phase is shown in the diagram. It will be noted that, between the fault and the generator there is no residual current, and the output of the generator can be resolved into equal positive and negative sequence components. The currents between the fault and the transformer are in phase in all three lines. They are zero sequence currents and would combine in a residual current network to give 3I, the actual current in the fault. It will be observed that no part of the faulty line carries a current equal to the current in the fault. We have seen that this fault current can be resolved into equal positive, negative and zero sequence components, and the conditions indicated in Fig. 74 are seen to justify this conception since the positive and negative sequence components are manifestly supplied by the generator, while the zero sequence component is supplied by the transformer.

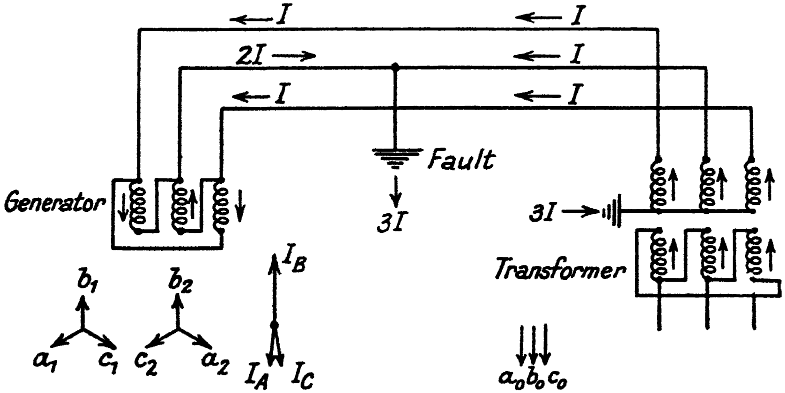


FIG. 74.—EARTH FAULT CURRENTS.

A somewhat more complicated example is shown in Fig. 75. Here we have a generator feeding a line through a delta/star step-up transformer, and to the end of this line is connected a power transformer. The neutrals of both transformers are earthed. The currents flowing in the system due to an earth fault in line B are marked in on the diagram. Between the fault and the power transformer the currents are zero sequence only. Between the fault and the generator, the line currents comprise positive, negative and zero sequence components, the zero sequence components in this portion of the system combining to produce a residual current equal to $3I_1$, the current in the earth connection to the neutral of the step-up transformer. In this case zero sequence currents are supplied by each transformer.

It should be carefully noted that in each of the above examples, the characteristics of the system of currents change at the fault, notwithstanding only one line is earthed. Referring again to Fig. 74, we see that, according to the symmetrical components theory, positive and negative sequence components disappear from lines A and C when the fault is reached, and the place of these components is taken by the zero sequence component from the transformer. This zero sequence component virtually flows in three lines and passes from them into the fault.

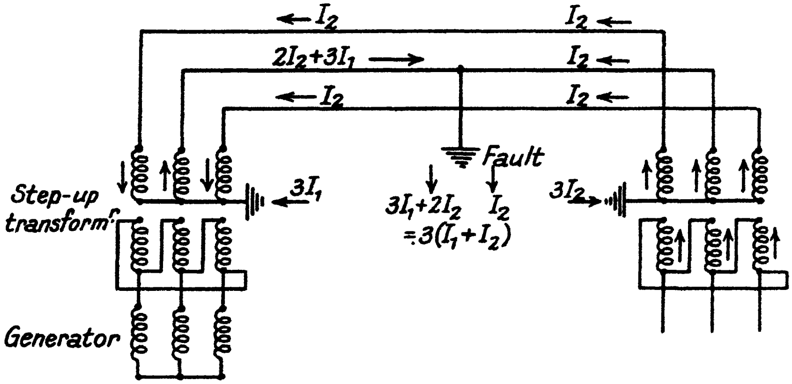


FIG 75.—EARTH FAULT CURRENTS IN A SYSTEM WITH TWO EARTHED NEUTRALS.

Conditions which give rise to Negative and Zero Sequence Components.—The theory of symmetrical components which relates to the incidence of negative and zero sequence components may be summarised as under :—

(1) Negative sequence currents are produced by unsymmetrical loading or by short-circuit faults.
(2) Zero sequence currents are produced by earth faults.
(3) Only positive sequence voltages are produced by rotating plant.
(4) Negative and zero sequence voltages are only produced respectively by negative and zero sequence currents, in a system with symmetrical line impedances.
(5) Positive and negative sequence currents can be generated by an alternator, but no zero sequence currents unless its neutral is earthed.
(6) Each earthed point on a system is a source of supply of zero sequence currents.
(7) Each sequence current circulates through the system in a manner depending on its sources of supply and independently of the circulation of other sequence currents.
(8) No zero sequence current can flow into or away from an unearthed machine or transformer.
(9) The reactance of transmission lines is the same to positive and negative sequence currents, but greater to zero sequence currents.
(10) The impedance of rotating machines to negative sequence currents produced by negative sequence voltages is very much less than the impedance to positive sequence currents.

Calculation of Fault Currents.—The conception of impedances of generators, transformers, and transmission lines to negative and zero sequence currents is of considerable importance in the technique of the calculation of the distribution of fault currents in extensive networks. A complete consideration of this technique falls without the scope of this book, but a short preliminary explanation of basic principles may interest the student.

The fundamental theorem in the symmetrical component method of network calculation is *that the total current flowing into an earth fault is given by the expression,*

$$\frac{3E}{Z_1 + Z_2 + Z_0}$$

where E is the phase to neutral voltage and Z_1, Z_2, and Z_0 are respectively the positive, negative, and zero sequence impedances of the whole network from the sources of the supply to the fault. These component impedances are calculated by determining the sequence currents which would flow separately to an imaginary connection of all three lines of the system to earth at the fault position. These sequence currents are purely fictitious, and in calculating them, generators are deemed to be sources of positive and negative sequence currents, while earthed generators and transformers are considered as sources of zero sequence currents. The network for the calculation of positive and negative sequence currents is thus usually different from that applicable to the zero sequence currents. When these fictitious sequence currents have been determined, the corresponding values of the impedances Z_1, Z_2, and Z_3 are given by the ratios of the phase to neutral voltage to these currents. This theorem has been proved rigorously by Fortescue and its application may be illustrated by a consideration of the simple case of a three-phase generator with an earthed neutral supplying current to an earth fault near to one of its terminals.

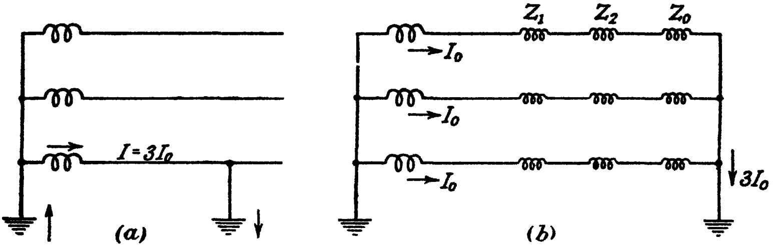


FIG. 76.—GENERATOR WITH EARTHED NEUTRAL

This condition is shown in Fig. 76 (a). The fault is in phase C, and the actual current flows through one winding of the generator and through earth, as shown. The equivalent network according to the theorem referred to is shown in Fig. 76 (b). The current flowing to earth, in this equivalent circuit, is conceived to be due to a simultaneous generation of positive, negative, and zero sequence components. The positive and negative sequence components, being balanced, cancel at the common connection and give a zero resultant. The zero sequence components being all in phase, combine at the common connection and flow, via earth, back to the generator neutral. The circuit, Fig. 76 (b) is purely fictitious, and merely illustrates the method of calculation which has been briefly described.

As a simple application of Fortescue's theorem we may consider the effect on the maximum earth-fault current from a generator with an earthed neutral of other generators connected in parallel with it. The maximum current delivered to an earth fault by the single generator alone is, as we have seen, given by the expression,

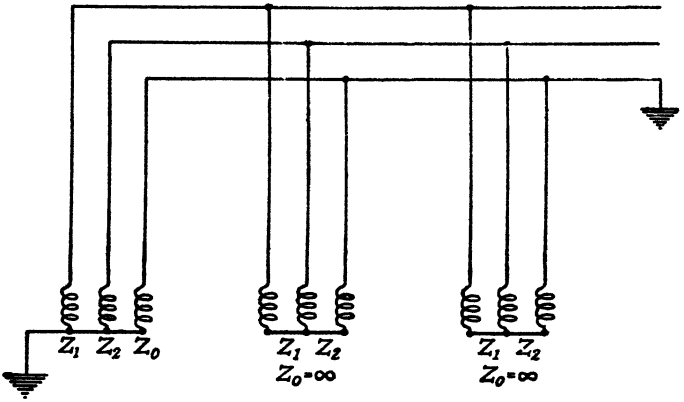


FIG 76A.—EARTH FAULT CURRENT FROM SEVERAL GENERATORS IN PARALLEL

$$I_1 = \frac{3E}{Z_1 + Z_2 + Z_0}$$

where Z_1, Z_2, and Z_0 are the sequence impedances. Suppose, now, that (n–1) similar generators with free neutrals are connected in parallel with the earthed machine, Fig. 76A. The zero sequence impedance of each of these generators is infinite. The positive and negative sequence impedances are each Z_1 and Z_2 respectively. All generators can supply positive and negative sequence currents and the corresponding impedances to the fault position will be Z_1/n and Z_2/n respectively. *The zero sequence impedance will remain* Z_0. *Thus the value of the current on the fault will be*

$$I_2 = \frac{3En}{Z_1 + Z_2 + nZ_0}$$

Thus the fault current will be increased by the connection of the (n–1) generators in parallel in the ratio

$$\frac{n(Z_1 + Z_2 + Z_3)}{Z_1 + Z_2 + nZ_3}.$$

If the rating of the unearthed generators is large in comparison with that having its neutral earthed, this ratio will approximate to the value

$$\frac{Z_1 + Z_2 + Z_0}{Z_0}$$

Now the positive sequence impedance of a generator is considerably greater than either its negative or zero sequence impedances. In a salient pole machine the ratio Z_1/Z_2 may be of the order 5, and Z_1/Z_0 of the order 10. Using these values in the above expression, we see that the steady earth fault current delivered by a generator may be increased to the order of 12-fold by the connection in parallel with it of large unearthed generator capacity.

If the single generator is earthed through a limiting resistance, the value of Z_0 will include three times the value of this resistance, since it carries three times the zero sequence current. This increase in the value of Z_0 will reduce the ratio of fault current increase by the connection of unearthed machines in parallel.

CHAPTER V

RELAYS

General Remarks on Relays.—A relay used for automatic protection may be defined as an electrical movement operated by current or power which opens or closes a local circuit when the current has a specified magnitude, or bears a specified relation to the voltage of the main circuit with which the relay is associated.

In regard to underlying principle of operation relays may be divided into two main classes: thermal and electromagnetic. Electromagnetic relays may be further divided into the following sub-classes:

(a) *Attracted armature,* in which the movement consists essentially of an armature moved by the attractive force of the magnetic field set up by the current in the relay winding.

(b) *Moving Iron,* in which the movement consists essentially of a pivoted iron member and is generally similar in construction to a moving iron measuring instrument.

(c) *Induction,* in which the moving member is a disc or bell of conducting material free to rotate in two alternating magnetic fields which are separated both in space and in phase.

(d) *Dynamometer,* in which the moving member is a coil free to rotate in a magnetic field.

As regards their function relays may be classified as follows:

(a) *Under-voltage and under-current,* in which operation takes place when the current or voltage falls below a specified value.

(b) *Over-voltage and over-current,* in which operation takes place when the current or voltage rises above a specified value.

(c) *Directional,* in which operation takes place when the component of the current in phase with the voltage assumes a specified magnitude and a specified direction in relation to the voltage.

(d) *Distance*, in which the operation is governed by the ratio of the voltage to the current or to the component of the current having some specified phase relation to the voltage.

An important characteristic of a relay, additional to the magnitude of the current required to operate it, is the time delay between the incidence of the operating current and the completion of the operation which results in the opening or closing of the local circuit. Relays can be classified, with regard to their timing characteristics, under the following heads:

Instantaneous, in which complete operation takes place after negligibly small interval of time from the incidence of all values of the operating current slightly in excess of the minimum

Definite Time Lag, in which the time delay between incidence of the operating current and completion of the operation is sensibly independent of the magnitude of the current.

Inverse Time-Lag, in which the time delay is approximately inversely proportional to the difference between the actual current and the minimum current required to cause operation. With the majority of relays of this class, the time-lag tends to a definite minimum value as the current is increased without limit.

It is customary to provide in all relays means for varying the value of the current required for operation, and also, in relays giving time delays, means for varying this delay. The nominal values of the current to give operation and of the time delays are known as the settings. With relays in which the time delay decreases as the current increases, but tends to a definite minimum, this minimum time-lag is taken as the basis of the nominal time setting.

With respect to the auxiliary circuit, relays can be divided into two classes, those in which the auxiliary circuit is normally open and those in which it is normally closed. The first class, those in which operation of the relay closes a circuit, are used when the circuit-breaker associated with the relay is automatically tripped by current from a battery source of supply. The auxiliary circuit of such a relay is shown in Fig. 77. The second class, in which operation of the relay opens a circuit, are used when the source of power for automatically tripping the breaker is derived from the current transformer feeding the relay coil. The auxiliary circuit of such a relay is shown in Fig. 78. Here the relay contacts normally short-circuit the trip coil, and operation of the relay removes the short-circuit, and allows the current from the transformer to flow into the trip coil and so to open the breaker. The switch of a circuit opening relay is almost invariably composed of two mercury cups into which a bridging conductor dips, the operation of the relay lifting the bridge piece out of the mercury. The switch contacts of a circuit closing relay are usually of metal, and such relays are often provided with a second switch which by the operation of the relay is caused to fall, either by gravity or by a spring loading, into a second pair of contacts of greater area and robustness than those bridged directly by the relay movement. Such auxiliary switches usually remain in the closed position till they are re-set by hand, notwithstanding the relay movement has returned to its normal position. Relays having an auxiliary switch of this kind are designated hand-resetting, while those in which the auxiliary switch is opened as the movement returns to its normal position are known as self-resetting.

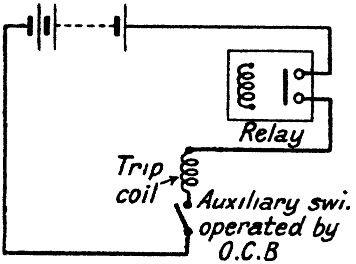


Fig 77 —Circuit-Closing Relay

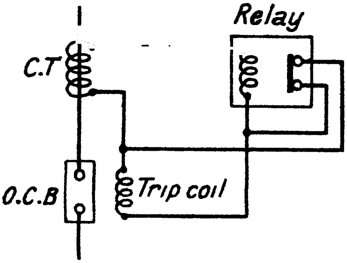


Fig 78 —Circuit-Opening Relay

Although a circuit-closing relay initiates the supply of current from the tripping source to the circuit-breaker trip coil, this current is never interrupted at the relay contacts. An auxiliary switch, shown in Fig. 77, coupled to the breaker mechanism, is invariably provided, so that the tripping current is interrupted by this switch, simultaneously with the opening of the breaker, and before the relay movement commences to return to its normal position.

If a circuit closing relay is designed for very sensitive and rapid operation its moving element will be light and undamped, and it will tend to vibrate in response to the alternations of the attractive force of the current or power operating it. This will tend to set up chattering and, hence, uncertainty of contact in the auxiliary circuit switch. For this reason relays of this type are generally provided with light and springy contacts which close the operating coil of a small contactor in the relay case. This contactor, once energised, remains closed by its own attractive force, and establishes the tripping circuit of the associated breaker.

Time Limit Fuses.—Although what is usually called a time limit fuse is not a relay, yet this device performs a function of the same kind as that proper to a relay in that it can be used to interrupt a circuit with a time-lag which bears a definite relation to the current passing through it. The time limit fuse is usually employed in the manner shown in Fig. 79. Here is a circuit comprising a current transformer, an oil circuit-breaker shunted by a time limit fuse, and an ammeter. So long as the fuse link is intact, this link diverts practically the whole of the secondary current of the transformer from the trip coil. The burden of the transformer in this condition is then limited to the impedance of the fuse, instrument and connecting leads. If the secondary current of the transformer rises to a value which is in excess of that which the fuse can carry indefinitely, this fuse melts, and the current passes into the trip coil. As this coil is so designed that the breaker will operate when the current in the coil is well below that required to melt the fuse,

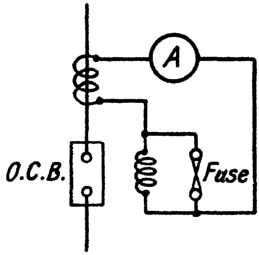


FIG. 79.—CONNECTIONS OF TIME LIMIT FUSE.

tripping of the breaker takes place immediately the fuse circuit is interrupted. The time-lag between the incidence of the excess current and the tripping of the breaker is thus governed by the characteristics of the fuse.

The constancy of the time-lag of a fuse with a fixed value of the current through it depends upon the construction of the fuse carrier being such that the fusible link is supported so that it is entirely surrounded by air in an enclosed chamber. The cooling of the fuse link during the time that the excess current is passing through it will then be due to radiation only, and the uncertain rate of cooling due to convection or to conduction by contact of the fuse with the material of the fuse holder will be quite small. Fig. 80 shows a typical time limit fuse the design of which is such that the fuse link is readily renewable. A length of glass tubing is cemented at each end into two cubical terminal blocks, drilled for the passage of the fuse wire, which wire is clamped externally to the terminal blocks by the small screws shown.

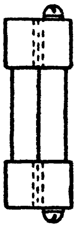


FIG. 80.—TIME LIMIT FUSE.

The connection between the temperature θ of a fuse carrying a constant current I, and the time t during which this current has been flowing, can, if the resistance R of the fuse be assumed constant, be expressed by the well-known exponential formula :

$$\theta = \theta_1 \left(1 - e^{\frac{-at}{s}}\right)$$

where a is a heat emission constant, s the thermal capacity of the fuse, and θ_1 the limiting temperature to which the fuse would attain if it did not melt. At this temperature :

$$a\theta = I^2R$$

thus

$$\theta = \frac{I^2R}{a}\left(1 - e^{-\frac{at}{s}}\right).$$

If θ be the fusing temperature of the wire, we have an expression connecting I and t which, however, neglects the heat required for fusion, and which, as we have observed, is based upon the faulty assumption of constant resistance.

The exponential equation is not at all easy to manipulate, but a function connecting I and t can easily be found, the graph of which is of the same form as that of the exponential formula. Examining this formula we find that as t increases without limit, θ approximates to the limiting value I^2R/a, while, with small values of t, as $e^{-\frac{at}{s}}$ is equal to $1-\frac{at}{s}$, the relation between θ and t is given by the equation

$$\theta = \frac{I^2Rt}{s}.$$

A simple algebraic function which has these characteristics is

$$\theta = \frac{I^2Rt}{s+at},$$

and this function gives a hyperbolic graph for the relation between θ and t. This last expression transforms to

$$I^2R - a\theta = \frac{s\theta}{t}.$$

If I_0 is the current the fuse will just carry indefinitely without melting, then $I_0{}^2R = a\theta_1$, where θ_1 is the fusing temperature, and the time required for the fuse to attain this temperature with any value of the current is obtained by substituting $\frac{I_0{}^2R}{a}$ for θ. Thus:

$$I^2 - I_0{}^2 = \frac{s\theta_1}{Rt} = \frac{K}{t}$$

where K is a constant.

We can obtain a similar equation to this in another manner by equating the heat imparted to the fuse by the current, which is I^2Rt, to the sum of the heat lost by radiation, $a\theta_2t$ and that required to melt the fuse, H. Here θ_2 is the average temperature over the whole period during which heating takes place which governs the rate at which heat is radiated. This equation gives

$$t\,(I^2R - a\theta_2) = H$$

If θ_2 be assumed to be equal to θ_1, the fusing temperature, this equation becomes

$$I^2 - I_0^2 = \frac{H}{t}$$

and is similar to that obtained by an algebraic approximation to the exponential function.

If this equation is correct a graph connecting observed values of I^2 and $\frac{r}{t}$ should plot into a straight line, while the intercept cut off by this line on the I^2 axis should give the value of I_0^2. Actual time/current characteristics of fuses experimentally determined are shown in Fig. 81, from which it appears that the value of I_0^2 obtained from the above equation is less than the actual value.

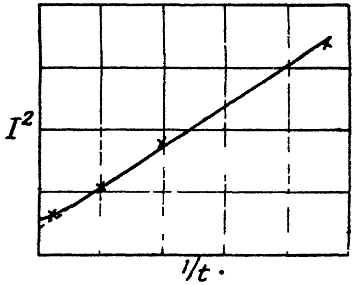


FIG 81 —CHARACTERISTIC OF TIME LIMIT FUSE.

If, therefore, two sets of values of I and t be observed experimentally, a time current characteristic can be obtained by plotting experimental values of 1^2 and $\frac{I}{t}$ and joining these points by a straight line, but this characteristic will give a lower value of the limiting current than that which the fuse will actually carry. This defect of the approximate formula does not lead to grave practical disadvantages, since it gives a safe value for the limiting current, and the method of obtaining the approximate characteristic by means of a straight line graph connecting points corresponding to observed values of I^2 and $\frac{I}{t}$ is a very convenient one.

The discrepancy between the value of I_0 obtained from the graph and that which the fuse will actually carry is due to the faulty assumption that the temperature θ_2 controlling the rate of heat radiation during the time the current is passing, is equal to the fusing temperature θ_1. This will only be true for values of I near to I_0, and when the value of I is considerably in excess of I_0, the average temperature will be less than θ_1.

Returning to the exponential formula, we can obtain, by a well-known algebraic transformation, a value for I_0, if we know two values of I corresponding to times the one of which is exactly one-half of the other. If these two values of the current be I_1 and I_2, then

$$I_0^2 = 2I_1^2 - \frac{I_1^4}{I_2^2}.$$

If we select from the straight line graph connecting observed values of I^2 and $\frac{I}{t}$ two values of I corresponding to two values of the time-lag, one of which is double the other, then, provided these time-lags are as small as is consistent with fairly accurate measurement, the values of I_1^2 and I_2^2 substituted in this equation will give a very close approximation to the actual value of I_0.

The time characteristic of a fuse in terms of primary current will be modified by ratio errors of the current transformer supplying it, and the effect of such errors will be to improve the characteristic from an operating point of view, since the time-lag in a given primary current will be increased by ratio error. In circumstances where accuracy of ratio of the current transformers is not very material from the point of view of accuracy, the characteristic of time limit fuses can be artificially improved by connecting resistance in series with them. This increase in the secondary burden will increase the ratio error of the current transformers, particularly with excessive primary currents, when an increase in the time-lag may be desirable. Alternatively, iron-cored reactors may be used to shunt the fuses, the reactors being so designed that they saturate with moderate overload values of the secondary current, and so divert a considerable fraction of this current from the fuses.

Thermal Relays.—The action of a thermal relay depends upon the deformation of a bimetallic strip or coil which is heated by a current proportional to that in the circuit which the relay controls. The bimetallic strip is composed of two metals having differing coefficients of expansion, and the strip may be heated by the passage of the operating current directly through it, by radiation and convection from a heating coil adjacent to it, or by immersion in an oil bath heated by the operating current. If the bimetallic strip is of considerable length and is arranged in the form of a coil the movement of the free end will be considerable, and this end may be connected to the switch arm which bridges the contacts of the auxiliary circuit. When the strip is short, so that the movement of the free end is small, this movement may be used to trip a spring loaded switch in the auxiliary circuit.

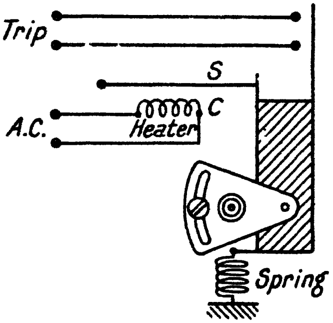


Fig 82 —Thermal Relay.

A typical thermal relay of the latter class is illustrated in Fig. 82. S is the bimetallic strip which is heated by the coil C of resistance metal fixed immediatly below it. A block of insulating material, pivoted as shown, carries the piece bridging the auxiliary circuit contacts, and also a piece which is held against the end of the bimetallic strip by the tension of a spring. When the heat communicated to the strip raises its temperature to a definite value, the end of the strip deflects upward and the pivoted member moves in a counter-clockwise direction so that the auxiliary circuit is closed. The depth of the engagement of the strip with the moving member can be varied by the rotation of a sector-shaped plate to which this moving member is pivoted, whereby the height of the pivot relative to the strip can be raised or lowered. If the pivot is raised, the engagement of the member with the bimetallic strip will be increased, a higher temperature will be required to deflect the strip sufficiently to allow the switch in the auxiliary circuit to close, and consequently a higher current will be required to cause operation of the relay.

The theory of the thermal relay is very similar to that of the time limit fuse, and an equation connecting the value of the current I with the time required for the relay to operate can be obtained by equating the heat communicated to the strip I^2Rt_1 to that lost by radiation $a\theta t$, plus that required to raise the temperature of the strip to the value required to close the contacts of the auxiliary circuit, $S\theta_1$. θ is the average difference between the ambient temperature and the final temperature of the strip which governs the rate of radiation loss, and θ_1 is the total rise of temperature of the strip during the time that the operating current is flowing. Thus:

$$t\,(I^2R - S\theta) = S\theta_1.$$

If I_0 is the current which will just fail to operate the relay, then

$$I_0{}^2R = S\theta,$$

and

$$t = \frac{S\theta_1}{R\,(I^2 - I_0{}^2)}.$$

The characteristic connecting t and I is thus similar to that of a time limit fuse, but due to the fact that a much larger quantity of heat is required to raise the strip to the temperature for operating the relay than is required to melt a fuse, the time-lags given by a thermal relay are considerably greater than can be obtained by a time limit fuse. This applies particularly to relays in which the bimetallic strip is heated indirectly as, obviously, only a fraction of the total heat produced by the current will be communicated to the strip. The difference in the time-lags obtainable from a time limit fuse and a thermal relay is shown in Fig. 83.

In the discussion of the time/current characteristics of fuses it was tacitly assumed that the rate of loss of heat by radiation and the total amount of heat required to melt the fuse was not affected by the temperature of the surrounding air. This assumption was justifiable by the fact that the ordinary variations in the ambient temperature likely to be experienced are small as compared with the increase in temperature required to melt the fuse. The case of a thermal relay is different from that of a fuse, in that the temperature rise of the strip required for operation of the relay is much less than that required to melt a fuse. We have already seen that the current I_0, which is the maximum which will fail to operate the relay, is connected with the temperature difference θ between the strip at the operating and the ambient air by the relation $I_0^2R = a\theta$. The actual temperature of the strip at which the auxiliary contacts are closed is independent of the air temperature, so that variations of the air temperature give rise to equal variations of θ. The limiting current thus varies as the square root of θ. If, for instance, the temperature of the strip required to operate a thermal relay is 100° C., then a variation in the ambient temperature from 10° C. to 40° C. will cause θ to decrease from 90° to 60°, and the value of I_0 will be decreased by the factor $\sqrt{\frac{60}{90}} = 0{\cdot}8$ approx. The variation in the limiting current caused by a variation in θ will also bring about a variation in the time t required for the operation of the relay when the current in it is in excess of the minimum value.

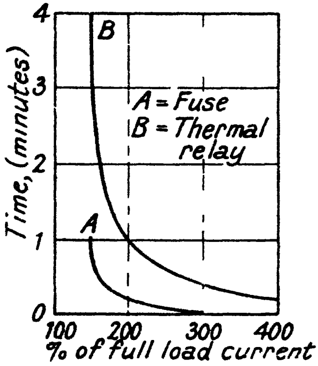


Fig 53.—Comparative Characteristics of Time Limit Fuse and Thermal Relay.

If, as is the case with the type of relay illustrated in Fig. 82, alterations in the nominal current settings are obtained by varying the amount of deformation of the bimetallic strip required to operate the relay, the difference between the temperature of the strip and that of the surrounding air will be proportional to the square of the current. A given alteration in the ambient temperature will thus produce a constant alteration in the square of the limiting current, and, if the variations in the ambient temperature are not excessive, the alteration in the minimum current which will operate the relay per degree variation in the ambient temperature is constant, whatever the value of the nominal setting may be. If, on the other hand, the relay operates at a constant temperature, and variations of the setting are obtained by shunting the heating coil, then the fractional variation in the value of the actual limiting current will be constant per degree variation in the ambient temperature, and the actual alteration of the minimum operating current in amperes will be greater for high than for low settings.

This feature of the thermal relay, that it is more sensitive with high than with low ambient temperatures, is advantageous when a relay of this type is used for the overload protection of an electrical machine, since it will permit the machine to carry heavier overloads in low than in high temperatures. The compensating feature, whereby the overload permitted by the relay tends to correspond with that which the machine can safely carry, is not, however, perfect. In the first place the temperature of the air surrounding the relay is not necessarily the same as that of the cooling air of the machine. Secondly, due to the fact that the operating temperature of the relay is often in excess of the maximum safe temperature of the machine, a given change in the ambient temperature will affect the current required to operate the relay to a lesser degree than the maximum current which the machine can carry indefinitely. If a thermal relay is required to have such a characteristic that its minimum operating current is for all values of the ambient temperature equal to the maximum safe current of the machine which the relay protects, then the operating temperature of the bimetallic strip in the relay should be 80° C., and the relay should be fixed in such a position that the temperature of the air surrounding it is the same as that of the cooling air of the machine.

The extent of the alteration of the time/current characteristic of thermal relay by variation in the ambient temperature is shown by the curves of Fig. 84. It will be observed that these curves refer to overloads applied after the relay has reached a constant temperature carrying the nominal full load current. It will be readily understood from the preliminary theoretical discussion of these relays that the temperature of the strip before the incidence of the overload affects the time-lag, but not the minimum operating current I_0. The value of this current depends only on the difference between the temperature of the bimetallic strip at operation and the temperature of the cooling air.

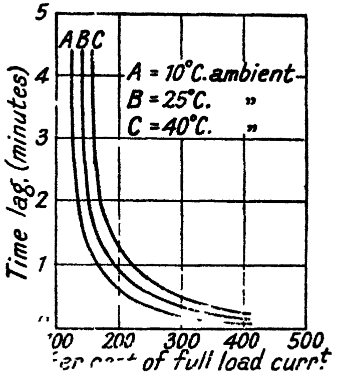


FIG. 84.—CHARACTERISTICS OF THERMAL RELAY FOR VARIOUS AMBIENT TEMPERATURES

The variation of the minimum operating current of a thermal relay caused by alteration of the temperature of the ambient air is sometimes considered a disadvantage, and relays are manufactured with a compensating device to give a minimum operating current which is independent of the temperature of the cooling air. This compensation is obtained by means of a second bimetallic strip, the deformation of which is responsive to the temperature of the cooling air, and to which the moving member of the relay is attached. Variations in the ambient temperature give rise to corresponding movements in the free ends of the main and the auxiliary strips so that the movement of the main strip required to operate the relay remains constant.

If the heating coil of a thermal relay is supplied from the secondary winding of a current transformer, the characteristic in terms of primary current will be modified by the performance of the current transformer. If the ratio of this transformer breaks down with moderate overloads, the time-lag given by the relay with a given primary current will be greater than would be the case if the transformer ratio remained in the neighbourhood of its rated value. For the purpose of overload protection, it is therefore advantageous to use, for the operation of a thermal relay, a current transformer whose ratio breaks down in overload conditions. For use in low-pressure circuits reactive shunts have been developed in America, the shunt consisting of a number of iron discs, each provided with a radial slot, threaded over the primary conductor. The relay winding is connected to this primary conductor in the manner shown in Fig. 85. The reactance of the shunt can be varied by adjustment of the assembly of the iron discs: if the radial slots are all in line the magnetic reluctance is a maximum, while if each disc overlaps the slots of its neighbours, the reluctance is a minimum. The variable reactance shunt behaves precisely as a current transformer with respect to the relay current, and by suitably choosing the number of discs, and the disposition of the radial slots, a reactance characteristic can be obtained giving similar results to the breakdown of ratio of a current transformer at any desired value of the overload.

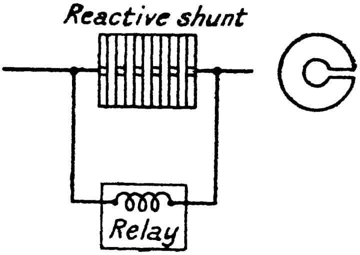


Fig. 85.—Reactive Shunt for Relay

Instantaneous Electromagnetic Relays.—These relays are of the simplest possible type, and the operation of the relay is brought about by the movement of either a pivoted armature, a plunger of a solenoid, or a pivoted iron vane, subjected to the action of a magnetic field set up by the operating current of the relay. A typical attracted armature relay is illustrated diagrammatically in Fig. 86, and the action of this relay is sufficiently obvious without further description.

Electromagnetic relays are, as regards their timing characteristics, usually of the instantaneous type, and if a time-lag is desired, when a relay of this type is used, such time-lag is generally provided by the use of one of the auxiliary devices which will be described hereafter. An instantaneous relay is described in the British Standard Specification, No. 142, for Electrical Protective Relays, as one which, with a current equal to one and a half times the setting value, will complete its operation with a time-lag not exceeding 0·1 seconds.

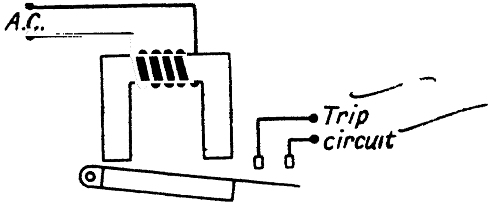


FIG. 86.—ATTRACTED ARMATURE RELAY.

Due to the inertia of the moving part, no relay can be truly instantaneous at any possible value of the current, and, although the time-lag of a nominally instantaneous relay will be very small for values of the operating current well in excess of the setting, the inertia of the movement will cause a sensible time-lag in the operation for values of the current only slightly greater than the setting.

If we consider that the attractive force on the moving element is proportional to the difference between the squares of the actual current I_1 and the minimum current I_0 which will operate the relay, and also assume as a very rough approximation that this force is constant with constant current for all positions of the movement, then we can equate this attractive force $K\,(I^2 - I_0^2)$ to the product of the mass of the movement M and its acceleration. The acceleration is therefore $K\,\frac{(I^2 - I_0^2)}{M}$, and if l is the total travel of the movement required to complete operation, we have, according to elementary principles,

$$t = \sqrt{\left\{\frac{2\,lM}{K\,(I^2 - I_0^2)}\right\}}.$$

This expression shows roughly the effect of inertia and length of travel of the movement on the time of operation of an instantaneous relay and indicates that to obtain maximum speed of operation both the length of the travel and the inertia of the movement must be reduced to the smallest possible values. The dependance of the time-lag upon the inertia of the relay movement has been utilised to obtain small time-lags in the Fawssett Parry relay. This instrument is of the moving iron type, and the movement consists of a pivoted iron vane which is caused to rotate against the torsion of a spring by the field set up by the operating current. The inertia of the relay can be varied without alteration of the controlling force of the spring by loading the movement with circular weights arranged concentrically with the axis of rotation.

It will be seen, from the approximate equation deduced above, that the time current characteristic of an electromagnetic relay is of a hyperbolic character. The time-lag will be quite appreciable when I is very little greater than I_0, although the magnitude of this time-lag for a given value of I will be more or less indefinite due to the uncertain influence of the static friction of the movement which has been neglected in the above discussion. The time-lags, in attracted armature relays particularly, will tend to diminish, as the operating current increases, quicker than is indicated by the approximate equation owing to the fact that the attractive force, for a given current, increases as the movement proceeds to position corresponding to completion of operation.

Induction Relays.—The essential components of relays of this class comprise a compound magnetic system in which are two alternating magnetic fields separated in time phase and in space, together with a pivoted disc which is free to move in the field of the magnet system. The torque on the disc may be conceived as being set up by the interaction of one of the magnetic fields with the currents induced in the disc by the other. This torque will be proportional to the product of the magnitude of the one flux, that of the current induced by the other, and the cosine of the angle of phase difference between the current and flux As the disc currents are in approximate phase quadrature with and are proportional to the flux producing them, the torque will, for a given frequency be proportional to $\Phi_1 \Phi_2 \sin \alpha$, where Φ_1 and Φ_2 are the two fluxes and α is the angle of phase difference between them.

The simplest method of obtaining the two fluxes satisfying the conditions mentioned above is found in the shaded pole pattern of induction relay. Although relays of this pattern are rarely manufactured to-day, there are a large number in use, and a short discussion of them will be desirable. The essential components of an induction relay are shown in Fig. 87, which represents diagrammatically a pivoted disc free to rotate in the air gap of an electromagnet, one-half of each pole of which is surrounded by a copper band or ring. The magnetic circuit can be considered to consist of two halves, the one with, and the other without a shading ring, and the exciting ampere turns due to the current in the winding being equal for these two halves. The ampere turns in the unshaded portion will, neglecting iron loss, be entirely effective in producing a magnetic flux in this portion. The ampere turns in the shaded portion will be expended, partly in producing a magnetic flux and partly in balancing the ampere turns in the shading ring due to this flux. If the shading ring be considered to be non-inductive, the currents in it will be in phase quadrature

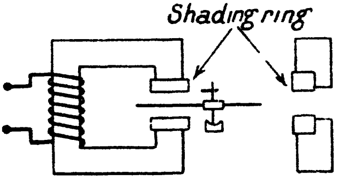
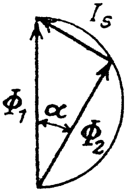


FIG 87—SHADED POLE INDUCTION RELAY.

with the flux threading it. The vector diagram for these conditions is shown in Fig. 88, Φ_1 being the flux in the unshaded part of the core, Φ_2 that threading the shading ring, while I_s corresponds to the current in this ring. As the torque is proportional to $\Phi_1\Phi_2 \sin \alpha$, it is also proportional to the area of the triangle on Φ_1 inscribed in the semicircle. The area of this triangle is a maximum, for a given value of Φ_1 when α is 45 degrees.

If the fluxes Φ_1 and Φ_2 were proportional to the current I in the relay winding, the torque would be proportional to the square of this current. While this relation holds for values of the current up to the rated full load of the circuit, magnetic saturation both in the core of the relay and also in that of the current transformer supplying it will result in the flux being approximately proportional to the square root of the current in overload conditions, so that the torque, in these conditions, will be approximate proportional directly to the current.



Φ_1 = Flux in unshaded section
Φ_2 = Flux in shaded section
I_s = Current in shading ring

FIG 88—VECTOR DIAGRAM FOR SHADED POLE RELAY

The movable member of the switch in the auxiliary circuit of the relay is closed or opened by the rotation of the disc under the influence of the operating torque. A permanent magnet is provided to give eddy current braking to the movement of the disc.

In the older patterns of induction relay, an arm, to which the switch contacts are attached, is raised by the relay disc by means of a flexible cord wound round the disc spindle. The minimum current which will move the disc can be regulated by varying the position of a weight in this arm, and the amount of travel of the disc can likewise be varied by adjustment of the normal position of the arm.

When a current, in excess of that just required to move the disc, passes through the coil of the relay, the resultant torque producing rotation will be equal to the difference of the driving torque KI and the control of the weight. This latter control will evidently be equal to KI_0, where I_0 is the current which will just initiate movement of the disc. The resultant torque is thus $K_1 (I - I_0)$. Neglecting friction the retarding torque will be due to the rotation of the disc in the alternating fields set up by the current, and in the field of the braking permanent magnet. This torque will be proportional to the angular speed ω, and to the squares of the fluxes. If B represent the permanent magnet flux then the retarding torque is $K_2\omega (I + B^2)$.

Thus when the disc is moving at a constant speed,

$$K (I - I_0) = \omega (I + B^2)$$

and

$$\omega = K \frac{I - I_0}{I + B^2}.$$

As the angle θ through which the disc must travel to complete operation is fixed for a given time setting, $\omega = \frac{\theta}{t}$, and

$$t = K\theta \frac{I + B^2}{I - I_0}.$$

If $I - I_0 = I_1$ then

$$t = K\theta \left(1 + \frac{I_0 + B^2}{I_1}\right) = t_1 \left(1 + \frac{I_0 + B^2}{I_1}\right).$$

According to the above theory, if values of t be plotted against $\frac{I}{I - I_0}$, the graph will be linear and t_1 will be the intercept of the graph on the vertical axis. Due, however, to the fact that the relation between flux and current in an induction relay is indefinite, the actual characteristic plotted in this way from experimental data, is only approximately linear.

This last equation shows that, as I increases without limit, t does not become vanishingly small, but approaches a minimum value t_1, which is equal to $K\theta$. The characteristic of the relay can thus be shown in the form

$$(I - I_0) (t - t_0) = t_1 (I_0 + B^2).$$

This equation shows that the graph of the characteristic is a hyperbola with vertical and horizontal asymptotes which are respectively $I = I_0$ and $t = t_0$. The graph is shown in Fig. 89. It will be noticed that the hyperbolic form of the characteristic does not depend upon the permanent magnet, and the form of the characteristic would be unchanged if the dynamic braking were obtained solely by the alternating flux. The term B^2 in the above expression merely increases the area enclosed by a vertical and horizontal ordinate. The chief function of the permanent magnet is to check the movement of the disc should the overload current in the relay coil be interrupted before the operation has been completed.

When considering the theory of the induction relay, the student should clearly grasp the distinction between the driving torque and the retarding torque due to rotation in the alternating magnetic fluxes. The driving torque is due to the two fluxes differing in both space and time phase and is set up by the attraction between one field and the eddy currents due to the other, which currents flow in a circuit whose axis is displaced in space with respect to the axis of the first field. The dynamic braking torque is due to the movement of the disc in the fields, and arises from the attraction between each field and the rotational eddy currents to which it gives rise. A braking torque would be set up by the rotation of the disc in the field of a magnet without a shading ring, but no driving torque could be set up by such a magnet as the condition requiring space and phase displacement of two fluxes would not be satisfied.

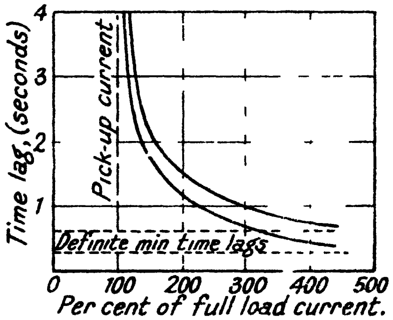


Fig. 89.—Characteristics of Induction Relay

The induction relay is essentially one whose time/current is of the inverse with definite minimum class, and it will be clear that if two relays are connected in series and have identical values of I_0 then, as the minimum times are proportional to the angular rotations required to operate the relays the one requiring the greater travel will for all values of the current operate before the other. It should also be noted that if the two relays in series are adjusted for different pick-up current values, then the characteristic of the relays for the higher current will be practically identical in shape with that of the low-setting relay, but it will be moved horizontally to the right in Fig. 89 by an amount corresponding to the difference in the pick-up current values. The operating time of the relay with the high setting will always be greater than that of the other but the difference of these operating times will continually decrease as the value of the operating current rises. Thus the difference in the operating times of two induction relays operated by the same current depends upon both current and minimum-time settings. These properties of the induction relay are very important and their application will be considered in detail hereafter.

The method of varying the setting of the relay by adjustment of the static retarding force has been discarded in relays of more modern design in favour of the method of using a tapped winding, the taps being brought out to a plug board and being so proportioned that the ampere-turns given by a current equal to the setting value are the same for all settings. The values of the current settings are usually specified in percentages of the rated full load secondary current of the current transformer with which the relay is used. According to modern convention the current setting of a relay with an inverse time characteristic corresponds to the minimum current which will set up rotation of the disc. This value of the actual operating current is known in America as the " pick-up current." The convention formerly in use in this country was that the setting value of the current was that which, flowing in the relay, would give a specified time-lag which was generally about 10 to 15 times the minimum time-lag. According to this convention the relay disc would commence to move with a value of the current less than the setting value. Although there are a number of induction relays in use the setting values of which are marked in this way, the settings of modern relays correspond, as stated above, to the pick-up currents, or those which are just sufficient to initiate rotation of the disc and ultimately to close the trip circuit contacts.

The portion of the core of a shaded pole relay movement which is embraced by the shading ring, with the coil, evidently constitutes a current transformer, and the phase of the resultant flux in this core is modified, with respect to that of the flux in the unshaded part of the core, by the magnetising ampere turns of the secondary circuit. It is customary in modern patterns of induction relays for the secondary circuit of the relay core to embrace the whole of this core, and for this circuit to be composed of a second winding, the current in which sets up a flux in an auxiliary magnetic circuit, disposed spatially with respect to the main circuit in a manner requisite for the production of a torque on a disc which rotates in both fields.

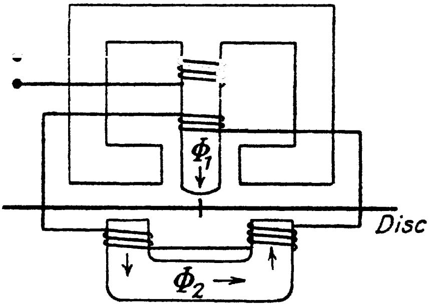


Fig. 90.—Double-Winding Induction Relay.

A relay of this pattern is illustrated diagrammatically in Fig. 90, and the vector diagram corresponding is shown in Fig. 91. This diagram, it will be seen, is similar to that already studied in connection with current transformers, the difference between the relay and the transformer and the relay being that, due to the air gap, the exciting current of the relay is relatively much larger than that of the transformer. The current in the secondary circuit is taken into the winding on the auxiliary lower magnet, and the flux Φ_2 induced by this current, is approximately in phase with it, but differs in phase from the main flux Φ_1 by an angle α. The driving torque, due to the two fluxes

Φ_1 and Φ_2 and the difference of phase, α, between them, is set up in a manner exactly the same as has been explained in the discussion of the shaded pole relay. Another modern relay, based on exactly the same principle, is shown diagrammatically in Fig. 92. Here the moving element is bell-shaped, and the auxiliary magnetic circuit is spatially at right angles to the path of the main flux Φ_1.

The difference between the pattern of relay just described and the shaded pole type is very important as, by using the current in the secondary circuit of the relay to produce the auxiliary flux Φ_2, a much greater angle of phase separation α between Φ_1 and Φ_2 can be obtained than in the shaded pole relay, in which the angle α corresponds to that between Φ_1 and Φ_p in the vector diagram, Fig. 88. As the torque given by the relay is proportional to sin α, the double winding pattern is in this respect, superior to the shaded pole pattern.

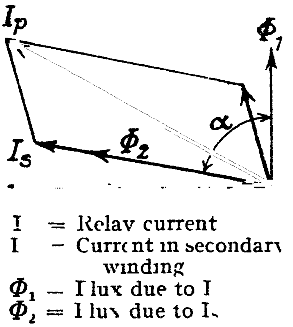

I_p
Φ_1
α
I_s
Φ_2
I_p = Relay current
I_s = Current in secondary winding
Φ_1 = Flux due to I_p
Φ_2 = Flux due to I_s

FIG. 91.—VECTOR DIAGRAM FOR DOUBLE-WINDING INDUCTION RELAY

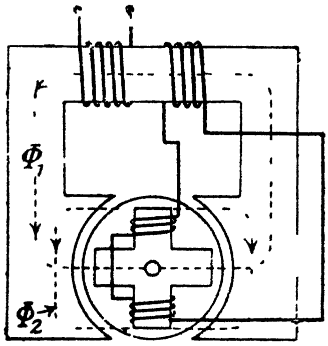


FIG. 92.—DOUBLE-WINDING INDUCTION RELAY

There is a further interesting and important feature of the double-winding pattern of induction relay, and this is that the operation can be controlled by modification of the secondary circuit. If this circuit is opened, then no auxiliary flux is set up, however great may be the value of the primary current, and no torque will be produced. A double-winding pattern of induction relay can, therefore, be made inoperative by opening the secondary circuit.

The relays illustrated in Figs. 90 and 92 differ in some other details from the shaded pole pattern. The static control is obtained by a spring, instead of a weight, and the contact piece bridging the switch contacts is attached directly to the spindle of the moving element. The method of varying the current setting by varying the number of turns of the primary winding is also employed. The time setting is varied by adjustment of position of a stop against which the control spring holds the movement in normal conditions. The use of a control spring instead of a weight gives a retarding torque which increases as the rotation of the moving element proceeds; and this modifies to some extent the theory of the induction relay set out above. The effect of the control spring is, however, small, and the relation of the time-lag to the operating current closely conforms to the hyperbolic law which has been deduced on approximate grounds.

In some modern patterns of induction relays the contact piece which bridges the trip circuit contacts is not attached directly to the main rotating element, but to a toothed sector which gears with a pinion on the spindle of this element. By the use of this gearing a considerable amount of rotation of the disc is required to move the sector piece sufficiently to close the trip contacts, and long minimum time-lags are more readily obtainable than if the trip circuit switch is directly connected to the disc spindle.

Relay with Linear Time-Current Characteristic.—The inverse with definite-minimum time characteristic of the induction relay is one which is useful in many circumstances, but in some conditions the minimum time feature is a disadvantage where it is desired that heavy short-circuits shall be cleared instantaneously. A modified design of overcurrent relay has recently been evolved in America, the time-lag of which diminishes from a fixed value at the setting value of the current proportionally to the excess of the current over this setting value, till for a specified value of the current the time-lag disappears.

The definite minimum time feature of the induction relay is, as we have seen, due essentially to the self-braking effect of the fluxes which provide the driving torque. In the relay with the linear characteristic the driving element consists of a solenoid the plunger of which is connected mechanically to the rotating disc by a spring coupling. The usual restraining force provided in an induction relay by a weight or spring is not used, but the force due to the solenoid is assisted by that of a spring. Operation of the relay is controlled by an auxiliary movement which, in its normal position, locks the main movement, but which unlocks this movement and allows rotation of the disc when the current in the auxiliary movement reaches the setting value. The effect of the spring coupling of the main movement to the rotating disc is to avoid the flattening of the characteristic curve at heavy overloads. If the overload is small, the force exerted by the driving element is small and the disc starts to rotate in the field of a permanent magnet, as soon as the driving member moves. The speed of travel of the solenoid is thus controlled throughout by the eddy current brake. With heavy overloads the solenoid moves against the reaction of the spring through a certain distance before the brake disc attains its steady speed. At a certain value of the overload, the travel is completed before the disc rotates and the operation is instantaneous.

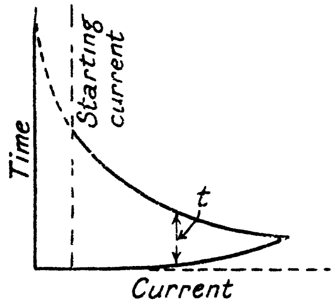
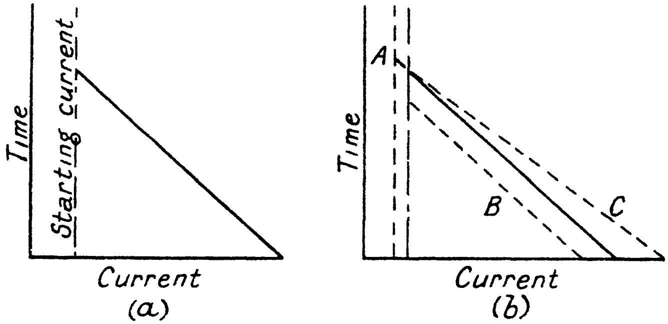


FIG. 93.—ILLUSTRATING METHOD OF OBTAINING A LINEAR TIME-CURRENT CHARACTERISTIC.

The effect of the spring which assists the action of the movement is that of a negative control, and virtually shifts the natural hyperbolic characteristic to the left as shown in Fig. 93. The dotted portion of the curve is rendered nugatory by the action of the locking device. The effect of the spring coupling is to cause the axis of zero time to bend upward to meet the characteristic curve as shown in the diagram. The resulting characteristic is very approximately linear, as shown in Fig. 94 (a).

A relay of the pattern described allows of three independent adjustments. The minimum current which will operate the relay can be adjusted by variation of the ampere-turns in the coil of the auxiliary device which unlocks the main movement. Alteration of the travel of the movement required to close the trip contacts has the effect of shifting the characteristic curve in a horizontal direction without varying its slope, while a variation of the ampere turns on the main driving member will vary the slope of the curve without affecting the value of the setting current. The three variable settings are illustrated in the curves of Fig. 94 (b). A shows the extension of the curve to the left, corresponding to an increase in the sensitivity of the auxiliary movement which unlocks the main movement, B shows the shift of the curve resulting from a reduction of the amount of travel required to close the trip contacts, while C shows the alteration of the slope of the curve resulting from a reduction of the effective number of turns in the solenoid of the main driving movement.



(a) (b)

FIG 94.—ADJUSTMENTS OF LINEAR CHARACTERISTIC

Directional Relays.—In the relays hitherto considered the working forces have been derived from the interaction of magnetic fields derived from the current in the relay windings. These working forces are, except as modified by magnetic saturation, inherently dependent upon the square of this current. The direction of the working force is therefore independent of the direction of the current. In a relay which is to be responsive to the direction as well as to the magnitude of the current, one of the magnetic fields which produce the driving torque must be derived from a source other than the operating current. Accordingly directional relays are essentially wattmeters, and the direction of the torque set up in the relay depends upon the direction of the current relative to the voltage with which it is associated. Thus a directional relay is inherently a power relay, and, excepting so far as it is modified by special devices, its response will be to a specified value of the power flowing in a specified direction.

The simplest forms of directional relays are modified watt-hour meter movements, and they may be considered to be derived from the over-current induction relay already described by substituting a voltage coil for the main current coil, removing the secondary winding on the main electro-magnet, and passing the operating current into the winding on the auxiliary magnet. The voltage coil is connected directly to the source of exciting voltage and the flux due to the current in this coil will be very nearly 90 degrees lagging on the voltage, while the flux due to the current coil will be very nearly in phase with the operating current. As the torque is proportional to $\Phi_1 \Phi_2 \sin \alpha$, and α is $(90 - \phi)$ this torque will be proportional to $I V \cos \phi$, the power in the circuit. Power directional relays may be of the single-phase or of the three-phase patterns, the latter pattern consisting of two watt-hour meter elements with a common spindle. The control force for varying the setting is provided by a spring, the tension of which is adjustable, while varying time-lags can, as in the induction over-current relay, be obtained by adjustment of the amount of rotation required by the disc to close the trip contacts.

The current required to operate a directional relay, with a constant value of ϕ, will vary inversely as the voltage. Now the severity of a fault is assessed by the magnitude of the current in it, and not by the power carried by this current. Further, the incidence of a fault leads to a drop in the voltage on the parts of the system adjacent thereto. A wattmeter relay will therefore become less sensitive the greater the fall in voltage occasioned by the fault. It is highly desirable in many circumstances that the current required to operate a directional relay be approximately independent of the exciting voltage and dependent only on the current setting value. There are two methods in common use whereby the operation of a directional relay is rendered very nearly independent of voltage fluctuations.

Combined Directional and Over-Current Relay.—The simplest method of obtaining independence of voltage changes consists in the use of an induction current relay in conjunction with a directional wattmeter relay which is so sensitive that, with the lowest value of the voltage which may be anticipated in the severest fault conditions, sufficient torque will be produced by a current equal to the setting value to close the contacts of this relay. The two relay elements are so arranged that the tripping circuit controlled by them is not closed till two conditions are satisfied, (a) the current reaches the value corresponding to the setting of the current relay and (b) its direction is such as to operate the wattmeter relay. The simplest method of achieving these results is to connect in series the switches operated by the two movements, as the operation of one movement alone will then evidently fail to energise the tripping circuit. There is, however, an objection to this simple procedure which we will now explain. Conceive that a substation is supplied by three cables, through circuit-breakers each of which is controlled by a directional and over-current relay, the trip circuit switches of which are connected in series. Should a fault occur on one of these cables, then, as we shall see later, the relay combination controlling the breaker for the faulty cable will operate, and, after the lapse of the time-lag given by the over-current element, the breaker of the faulty feeder will trip. Meanwhile, current may have been fed into the fault by the remaining cables, and the over-current elements of the relays for these cables will operate and close their trip switches, but the breakers will not be opened as the direction of the fault current will be such as to hold the directional elements in the normal position. The instant the faulty cable is cleared, the fault current ceases to flow through the remaining cables, but the direction of the load current may be such that one of the sensitive directional elements of the relays for these cables operates and closes its switch contacts before the contacts of the over-current element, which have been closed by the fault current, have time to separate. A second breaker may thus be tripped by the improper operation of the relays.

An alternative arrangement of the two relay elements is to use the switch of the over-current element to close the voltage circuit of the directional element, which circuit would, in normal conditions, carry no current. A little thought will, however, make it clear that this arrangement is open to the same objection as applies to the one in which the switches of the two elements are connected in series.

The standard arrangement whereby the over-current and directional elements each control the tripping of the circuit-breaker associated with the relay is to connect the switch of the directional element in the secondary circuit of the over-current element. We have seen that no torque can be developed in a double winding induction relay if the secondary circuit is open. So long, therefore, as the flow of power is in the normal direction no operation of the over-current relay takes place. If the current reverses and attains a value equal to or in excess of the setting of the current relay, then, and then only, will both elements operate together, and, after the lapse of the time-lag given by the current relay, the switch of this element energises the trip coil of the associated circuit-breaker. The arrangements of the several circuits of a combined directional and over-current relay is shown diagrammatically in Fig. 95.

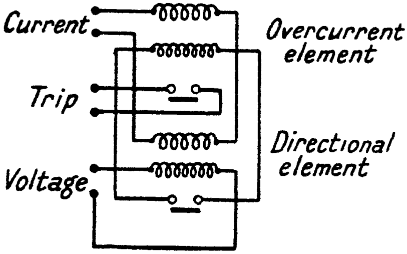


Fig. 95.—Directional Over-current Relay

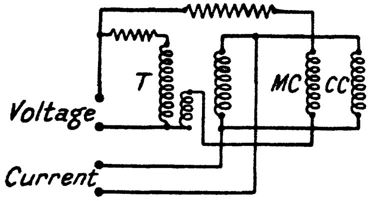
The combination of a sensitive directional relay with an induction current relay is very flexible. Variations of the current and time-lag settings are given by the current relay, and the sole office of the directional relay is to cause the current relay to be operative when the power flow is in the specified direction. The sensitivity of the directional element is such that it will be operated by a current corresponding to the lowest setting of the current element and with two per cent. of the normal voltage.

In certain circumstances it is required that the operation of the directional relay combination be instantaneous, and for such a condition it is necessary to use a current relay of the moving iron or attracted armature type. With a combination consisting of a directional relay and an instantaneous current relay, the contacts of the switches of these relays must be connected in series. The objection to this procedure which has been explained in connection with the use of an induction relay is not so serious with an instantaneous relay as, due to the quicker movement of these relays, the current element switch will probably open circuit before that of the directional element closed, should the conditions have been similar to those described on p. 146. If, however, the contacts of the instantaneous relay are hand-resetting, then the objection to connecting the two sets of contacts in series will apply and the combination of directional and instantaneous current elements must be used with care.

The construction of a directional relay energised by residual current and voltage differs in no way from those energised by line currents and voltages except that, as explained on p. 63, the voltage coil must be competent to stand three times the normal secondary line pressure. When the directional relay is energised by a residual current and a secondary current derived from a transformer in an earthing connection, both windings will be wound for the rated secondary current of the current transformers.

Compensated Directional Relays.—A wattmeter relay can be made to operate with a current which is approximately independent of the exciting voltage by incorporating some modification whereby the movement is acted upon by a torque derived from the voltage alone, in addition to the torque due to the watts. The supplementary voltage torque is constant in direction, and this direction is such as to hold the movement in the off position. A fall in the voltage thus decreases the hold-off torque due to this voltage and thereby makes the relay more sensitive to the wattmeter torque.

The characteristic obtainable by this method can conveniently be studied by considering in detail the electrical circuits of a modern directional relay of the dynamometer type. This instrument comprises an iron-cored electro-magnet on which are two windings, and which is arranged with an annular air gap in which a pivoted moving coil is free to rotate. The moving coil carries a current proportional to the voltage of the circuit in which the relay is connected. One winding of the magnet carries the circuit current, and the other a current, derived from a small transformer, which is proportional to the voltage. The internal connections of the relay are shown in Fig. 96. If the circuit power factor is unity the wattmeter torque is proportional to IV, the voltage hold off torque to V^2 and the static control is constant and equal, say, to w. Thus, when the relay operates,



T = Compensating Transformer.
MC = Moving Coil.
CC = Fixed Current Coil.

Fig 96 —Compensated Directional Relay.

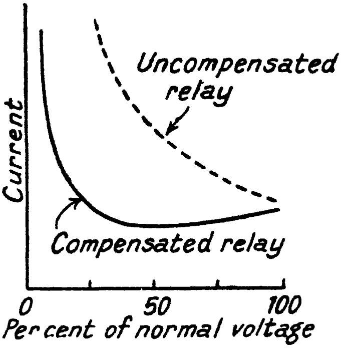


Fig 97.—Characteristic of Compensated Directional Relay.

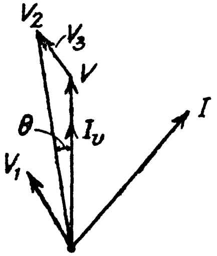
$$IV - aV^2 = w$$

whence

$$I = \frac{w}{V} + aV,$$

the first term of this expression for I increases and the second term diminishes as V diminishes, so that I remains approximately constant over a considerable range of variation of V.

In the relay illustrated the nominal current setting is $1\frac{1}{4}$A, and the current derived from the auxiliary transformer at the normal voltage is 1A. With a voltage which is a fraction n of the normal voltage this current will be n amperes. The static control is evidently equivalent to the torque given by a resultant current in the fixed coil of $\frac{1}{4}$A, at unity power factor and normal voltage. If V_1 be the normal voltage, then at a voltage of nV_1 and a power factor of unity, the wattmeter torque is nV_1I, the voltage hold off torque n^2V_1, and the static control torque $\frac{V_1}{4}$. Thus,



I = Main current.
V = Main voltage.
V_1 = Voltage on transformer winding.
V_3 = Voltage of tertiary winding
V_2 = Resultant voltage on moving coil circuit.
I_v = Current in moving coil.
θ = Lag of I_v on V_2.

FIG. 98.—VECTOR DIAGRAM FOR COMPENSATED DIRECTIONAL RELAY.

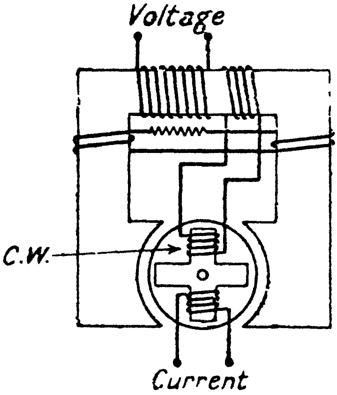


FIG 99.—INDUCTION DIRECTIONAL RELAY

$$nV_1I - n^2V_1 = \frac{V_1}{4}$$

and

$$I = \frac{1}{4n} + n.$$

The characteristic, connecting I and n, corresponding to this equation, is shown in Fig. 97, from which it will be seen that the relay actually becomes more sensitive as the voltage falls till n reaches a value of $\frac{1}{2}$. The corresponding characteristic for a non-compensated wattmeter relay is shown in the same diagram. If the voltage on the relay fall to five per cent. of the normal value, we find by substituting $n = 1/20$ in the above equation that the current required for operation is 5·05A, and only about four times that corresponding to normal voltage.

It will be observed in the diagram of connections, Fig. 96, that there is, in series with the moving coil circuit, a small tertiary winding on the transformer which furnishes the compensating current. The office of this winding is to correct for the lag of the moving coil current on the voltage applied to the relay. The compensating transformer is a reactive circuit and, being in series with a resistance, the voltage V_1 across its terminals will, as shown in the vector diagram, Fig. 98, lead on the applied voltage V. The E.M.F. which is added to V by the tertiary winding gives a resultant V_2, and th current in the moving coil produced by this resultant is shown as I_v, and is in phase with V.

A typical induction pattern of compensated directional relay is illustrated diagrammatically in Fig. 99. This relay is evidently a modification of the current relay shown in Fig. 92 (b), and the current in the compensating winding CW is derived inductively from the applied voltage in a manner which will be clear from the diagram. The resultant flux in the vertical limbs of the cross-shaped member is thus proportional to the difference of the current and a fraction of the voltage, and the principle of this relay is thus similar to the dynamometer relay already discussed, the radical difference between the two patterns being that in the dynamometer pattern the current proportional to the voltage is conveyed into the moving coil by conduction, whereas in the induction pattern, the current proportional to the voltage can be considered as being conveyed into the rotating member by induction. The office of the closed winding on the main electro-magnet in Fig. 99 is to modify the phase of the horizontal flux across the gap so that, with a power factor of unity, the currents induced in the bell by the voltage flux are in phase with the flux set up by current.

Distance Relays.—We have now to consider a type of relay in which the operation is governed, not by the magnitude of the current or power in the circuit with which the relay is associated, but by the ratio of the voltage of the circuit at the point where the relay is connected to the current flowing past this point. A relay so designed will operate when the impedance of the circuit on the side of the relay remote from the source of supply falls to a specified value. The application of relays of this class will be considered in detail in a subsequent chapter, but at this stage we may point out that the impedance of a supply circuit, reckoning from any point, is made up of the resultant impedance of the load, and the impedance of the connecting lines. This latter impedance is proportional to the length of these lines, and by adjustment of the impedance value required to operate a relay of the type now under consideration, to correspond to a figure equal to that of the connecting lines we have a device which, apart from minor limitations, will operate with a short-circuit on the connecting lines, when the impedance is less than that corresponding to the setting of the relay, but which will be inoperative for any value of an overload, or for a short-circuit on the consumer's side of the supply terminals, when the impedance will be greater than this setting value. As the setting of such a relay can be expressed in terms of the greatest length of transmission line which, when short-circuited, will cause operation, the designation distance relay is often given to instruments of this type. The simplest pattern of instantaneous distance relay is illustrated diagrammatically in Fig. 100. Here are two solenoids, energised respectively by the current and voltage of the circuit, the plungers of which are mechanically connected to a pivoted beam on opposite sides of the fulcrum. The trip circuit switch bridging piece is connected to the beam, and the arrangement is such that

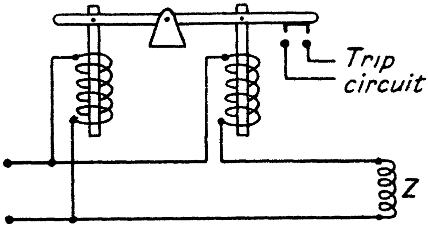


FIG. 100.—DEFINITE-IMPEDANCE RELAY

An interesting method of biasing which has been suggested as being applicable to a dynamometer type of current relay is shown schematically in Fig. 116. The dynamometer relay comprises two circuits, the one fixed, and the other movable, and operation of the relay, as in the wattmeter type, only takes place when the current in one circuit flows in a stipulated direction in relation to the other. As long as the secondary currents of the two current transformers shown in Fig. 116 are equal, the relative direction of the currents in the two circuits of the relay are such as to hold the movement in the normal position. If a difference current is superimposed on the straight-through current in one primary winding it will be seen that there are two parallel paths for the corresponding excess secondary currents, the one in the normal direction through one circuit of the relay, and the other, in a reverse direction through the second circuit of the relay and the shunting resistance. As the magnitude of the excess current increases in relation to the straight-through current, the resultant current in the second circuit of the relay will fall to zero and ultimately reverse. When the reversed resultant reaches a certain value the relay will operate. It is evident, therefore, that the magnitude of the excess current required to operate the relay depends for a given value of the setting and of the shunting resistance, upon the magnitude of the straight-through current. This method of biasing is only applicable to dynamometer relays and suffers from the disadvantage that a large fraction of the output of the current transformers is dissipated uselessly in the shunting resistance.

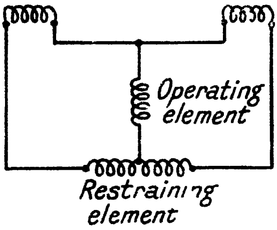


FIG. 117.—CONNECTIONS OF INDUCTION RATIO BALANCE RELAY

The biasing feature of an induction relay connected as shown in Fig. 117, is obtained by the use of two elements, each of which communicates a torque to the rotating element. The element which carries the main secondary current gives the restraining torque which tends to hold to movement in the normal position. The element carrying the difference current provides the torque which tends to close the trip circuit contacts. A relay of this kind will evidently operate with a value of the difference current which bears a sensibly constant ratio to the main secondary current. The mechanical control of such a relay will be quite small, and the various settings, stated in terms of the ratio of difference current required to cause operation of the relay, are obtained by alteration of the number of effective number of turns on the difference current winding. The constant ratio-difference characteristic is obtained in relays of American manufacture by the use of a magnetic circuit which is equivalent to a combination of two simple elements such that two torques are communicated to the disc, the one due to the difference current tending to cause operation of the relay, and the other due to the main secondary current tending to retain the movement in the normal position.

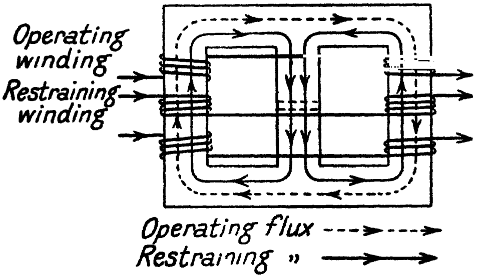


FIG 118.—BIASING TRANSFORMER.

A further method of obtaining a biased characteristic for a relay responsive to difference currents is by the use of an external device known as a biasing transformer. The principle of the biasing transformer is illustrated by the schematic diagram of Fig. 118. The transformer is seen to have three windings, a primary winding carrying the difference current to be transferred inductively to the relay, a secondary winding to which the relay is connected, and a restraining winding carrying the main secondary current. The windings are so arranged that the M.M.F.s set up by the primary and secondary windings are in the same direction round the outer magnetic circuit, while the M.M.F.s due to the two halves of the restraining winding tend to set up a magnetic flux which flows in opposite directions in this circuit, and which finds its return path through the central limb of the core. The flux due to the current in the restraining winding therefore induces no resultant E.M.F. in either the primary or the secondary circuits. The effect of this flux in the core is, however, to vary the primary exciting ampere turns required to produce the resultant flux round the outer magnetic circuit required to induce the necessary secondary E.M.F. necessary to cause operation of the relay. In other words, as the magnitude of the restraining current increases, saturation of the iron of the transformer proceeds, and the ratio of primary to secondary current increases. The difference current in the primary circuit required to produce the operating current of the relay in the secondary circuit thus increases as the restraining current increases. The relation between the difference current required for relay operation and the restraining current is shown graphically in Fig. 119. The two curves have reference respectively to a transformer with and without an air gap in the central limb of the core. Without an air gap the characteristic is seen to correspond to an approximately constant ratio of operating to restraining current. It will be seen that, by the use of an air gap, the value of the operating

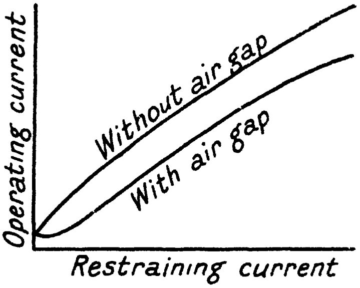


FIG 119.—CHARACTERISTIC OF BIASING TRANSFORMER.

current is approximately constant for values of the restraining current up to the rated full load current. The biasing feature is then restricted to overload conditions.

Over-Current Relays with External Restraint.—It is often desirable, on large transmission systems, to have some means of restraining over-current relays from operating when the value of the fault current exceeds that which the associated circuit-breaker is competent to interrupt. The fault current is finally cleared by a large breaker, situated on the network nearer the source of supply. A relay with the required characteristic is shown diagrammatically in Fig. 120. This relay has two components, the one an attracted armature element, set to operate at the maximum current which the associated breaker can handle. Operation of this relay opens the trip circuit. The second element is of the normal induction pattern and operation of this component closes the trip circuit. With a fault current whose value exceeds the setting of the attracted armature element, the induction element is manifestly incompetent to trip the breaker.

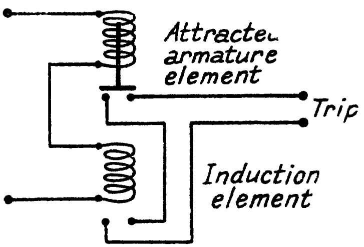


FIG. 120.—OVER-CURRENT RELAY WITH OVERLOAD RESTRAINT.

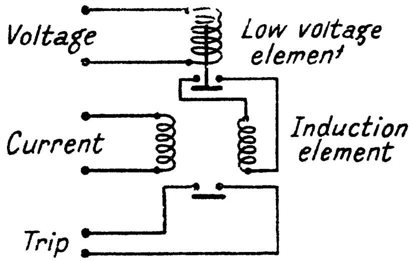


FIG. 121.—OVER-CURRENT RELAY WITH LOW-VOLTAGE RESTRAINT

In some circumstances it is desirable to prevent the operation of an over-current relay unless the voltage falls to a low value. A combination which satisfies this condition is shown diagrammatically in Fig. 121. Here a low voltage relay of the attracted armature pattern normally holds in the open position a switch in the secondary circuit of an induction over-current relay. This latter relay is thus restrained from operating with any current value, unless the voltage falls below the setting value of the undervoltage relay.

Translay Relays.—We have already explained that the operation of a two-circuit induction relay can be restrained by opening the secondary circuit. With this circuit open, the voltage induced in the secondary winding will depend upon the primary current, as the electrical and magnetic circuits of this pattern of relay are similar to those of an air gap current transformer. If the main circuits of two such relays of identical design carry the same current, equal voltages will be induced in the secondary windings. If these windings are so connected that these voltages are in opposition, no current will flow in the secondary circuits and no torque will be communicated to the rotor of either relay. If the currents in the main windings of the relays differ in value, unequal voltages will be induced in the secondary windings, and there will exist in the interconnected secondary circuit a resultant voltage due to which a current will circulate in this latter circuit. A torque will be set up in the rotor of each relay. The direction of the secondary currents will, however, be opposite in the two relays, and, consequently, the torque in one of the relays will tend to close the trip circuit, while, in the other relay, the torque will hold the rotor in the normal position. Induction relays, with their secondary circuits interconnected in the manner described, can, therefore, be used to indicate the main current transformer which carries the greater current. The designation "Trans-

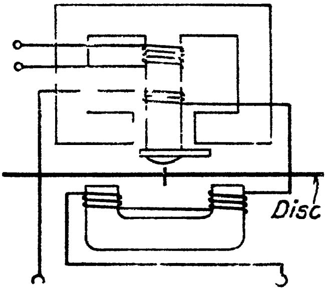


FIG. 122.—TRANSLAY RELAY

lay " applied to induction relays used in this manner is intended to indicate that the instrument is used both as a transformer and a relay.

The applications of the Translay relay will be dealt with in a later chapter, but a special feature of the instrument which provides a biasing feature, and also prevents operation by capacity currents, may here be described. The magnetic and electrical circuits of the relay are shown in Fig. 122, and it is seen that, in addition to the main winding and the secondary winding, there is a copper band, forming a single turn winding, on the salient pole of the upper magnet. The flux, due to the currents in the windings on this magnet, can be considered as the resultant of two components, one of which passes across the gap in the upper magnet, and the other of which passes out of the salient pole into the gap in which the disc rotates. The effect of the copper band is to cause the component which passes through it to lag in phase on the component which remains in the upper magnetic circuit, in accordance with the theory discussed on p. 134 in reference to the shaded pole relay. The vector diagram applicable to the relay is shown in Fig. 124. Φ_1 is the main flux giving rise to the secondary E.M.F. E_s, and Φ is the leakage flux, lagging in phase on Φ_1 due to the copper band. The currents induced in the disc due to Φ will be in phase quadrature with Φ as shown by the vector I_d.

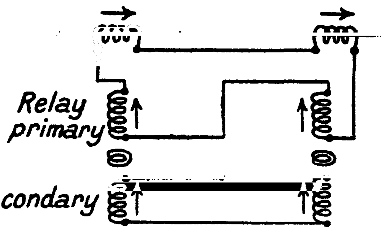
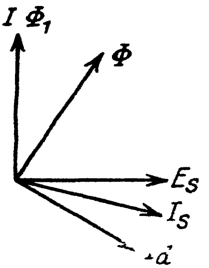


FIG. 123.—EXTERNAL CONNECTIONS OF TRANSLAY RELAYS.



Φ_1 = Main flux inducing E_s
E_s = Secondary E.M.F.
I_s = Secondary current.
Φ = Leakage flux in gap
I_d = Currents induced in disc by Φ.

FIG. 124.—VECTOR DIAGRAM OF TRANSLAY RELAY.

The torque will be proportional to I_sI_d, where I_s is the secondary current, and to the cosine of the angle of phase difference between these currents. The secondary current due to a difference in the secondary voltage of two interconnected relays will lag in phase on E_s. If, however, due to the capacitance of the leads connecting the secondary windings of two relays, a current flows into these leads with equal currents in the main windings, these currents will lead in phase on E_s, and when the angle between I_s and I_d exceeds 90 degrees, the torque will restrain the relay from operating.

The biasing feature of the Translay relay is obtained by the unsymmetrical situation of the copper band on the salient pole on the upper magnet, whereby a torque, restraining the relay from operating, is communicated to the disc, irrespective of the flow of current in the secondary circuit. This torque is set up in a manner exactly similar to that due to the secondary winding on the lower magnet. The restraining torque due to the copper band increases with the current in the main winding, and the difference current component required to operate the active relay thus increases with the straight-through component.

A later type of Translay relay embodies an additional biasing feature consisting of an auxiliary electro magnet producing a restraining torque on the movement which is connected in series with a capacitor to the secondary of an auxiliary current transformer in the main circuit of the relay. The impedance of the capacitor decreases as the frequency rises, hence the auxiliary biasing feature tends to stabilise the relay in high-frequency transient conditions, and so to prevent improper operation.

Definite Time-Lag Relays.—In relays of this type the time-lag is nominally independent of the current in the relay winding. The timing is, therefore, obtained by the movement of a member in response to a torque provided by a spring or weight, and the sole office of the current operated element is to release the timing element, which closes the trip circuit contacts after an amount of travel which is adjustable. The current operated element may be of the instantaneous solenoid or of the attracted armature pattern, and the value of the current required to effect the release of the timing element can be varied in the usual way. The combination is so arranged that, should the current in the release element be interrupted before the travel of the timing element is completed, the movement of this latter element is arrested, and it is immediately reset. The resetting of the timing member is usually automatic and effected either by a separate spring control from which it is disengaged by the release element, or by a separate voltage excited element which is only active while the disc is in a position other than normal and the release element is unexcited. The movement of the timing element is usually controlled by an eddy current brake, so that the time-lag is nearly proportional to the total travel of this element. The total time-lag of relays of this type is the sum of that given by the timing element, and that inherent in the release element. We have already explained that the time-current characteristic of a nominally instantaneous relay is really of an inverse character, and that, for values of the operating current only slightly in excess of the setting, the time-lag is appreciable. The time-lag of a definite time-lag relay only assumes the nominal value, therefore, when the current in the release element is sensibly in excess of the minimum required to effect operation.

The electrical features of constant time-lag relays are identical with those of instantaneous relays, and the only complications they exhibit are of a mechanical nature and connected with the timing element. The action of this element is readily comprehended by an inspection of the instrument, and considerations of the mechanisms used for timing purposes need not be described here.

Negative Sequence Relays.—A negative sequence relay is one which is associated with a filter network or other device so contrived that it is responsive only to the negative sequence component of a set of three-phase currents or voltages without a residue. Any type of over-current relay connected to such a resolving network as is described in Chapter IV will be a negative sequence relay. A wattmeter relay, energised by negative sequence current and voltage in the manner therein described, will respond to negative sequence-power. Just as a leakage relay responds to an earth fault uniquely, on whatever line it may occur, so a negative sequence relay responds to a short-circuit fault between lines, irrespective of the pair of lines between which the fault occurs, energised from star. A negative sequence relay will generally respond to earth leakage faults if it is energised from two star connected current transformers. If, however, the earth fault occurs on the line containing no current transformer, the relay will clearly be inoperative. When the zero sequence component is removed from a set of three-phase currents by connecting three current transformers in delta, the currents external to the delta will contain only positive and negative sequence components. As a residual contains a negative sequence component, a negative sequence relay energised from delta-connected current transformers will always respond to an earth fault of a magnitude corresponding to the setting.

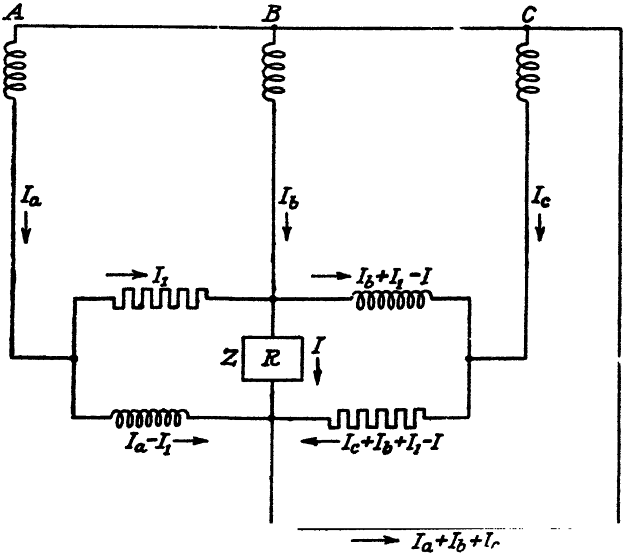


Fig. 124A—Negative Sequence Relay Network

A type of negative sequence protective arrangement developed by the Metropolitan-Vickers Electrical Co. is illustrated by the diagram of connections, Fig. 124A. This network is worthy of careful study. Here the four branches of the bridge arrangement are of equal impedances, and the phase angle of the reactive branches is 60 degrees, the other branches being non-inductive. Examining the network in a general way, it is seen that the currents from A and C transformers divide each into two parts, the one lagging and the other leading 30 degrees, if the relay impedance be assumed to be negligible. The positive sequence currents in the upper components of the bridge will combine and cancel the positive sequence current from B transformer. The negative sequence currents in these branches will be equal and opposite and cancel, and the negative sequence current from B transformer passes into the relay.

A detailed analysis of this network by symbolic algebra is instructive. The calculation is simplified by assuming that the impedance magnitudes of the four components of the bridge are all 1 ohm. Marking in the symbolic values of the currents in the network, we can at once write down the following EMF equations.

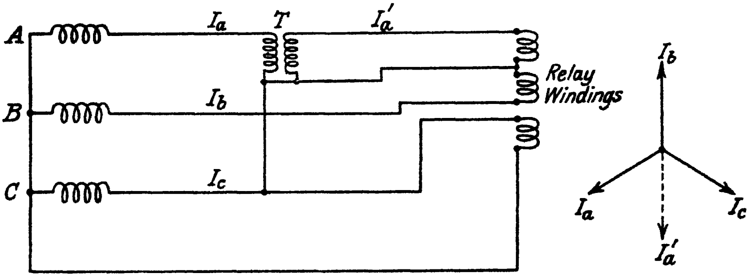


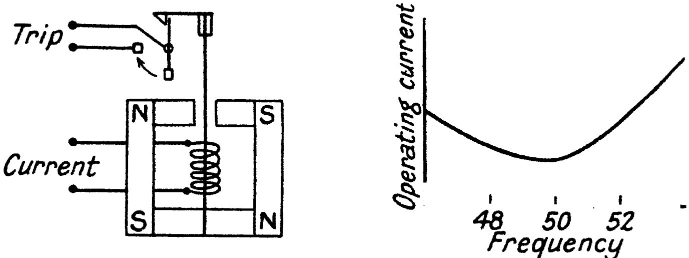
FIG 124B—NEGATIVE SEQUENCE AND LEAKAGE RELAY

$I_1 + h^{\frac{1}{2}} I_b + h^{\frac{1}{2}} I_1 - h^{\frac{1}{2}} I - h^{\frac{1}{2}} I_a - h^{\frac{1}{2}} I_1 - I_c - I_b - I_1 + I$
whence $2(1 + h^{\frac{1}{2}}) I_1 = h^{\frac{1}{2}} I_a - (1 + h^{\frac{1}{2}}) I_0 - I_0 + (1 + h^{\frac{1}{2}}) I$
and $I_1 + IZ = h^{\frac{1}{2}} I_a - h^{\frac{1}{2}} I_1$
whence $2(1 + h^{\frac{1}{2}}) I_1 = 2 h^{\frac{1}{2}} I_a - 2 IZ$,
combining the second and fourth equation we find

$$I\{ 2Z + (1 + h^{\frac{1}{2}})\} = (1 + h) I_a + (1 + h^{\frac{1}{2}}) I_b + I_c$$
$$= I_a + I_b + I_c + h^{\frac{1}{2}}(h^{\frac{1}{2}} I_a + I_b).$$

Thus the current in the relay is the resultant of three times *the zero sequence component and* $\sqrt{3}$ *times the negative* sequence current. The actual magnitude of the relay current depends upon the phase relation of these components. If the primary current is a pure residual, the relay current will depend upon the line carrying the residual. The magnitude of this current will depend upon the relay impedance, and its value can be symbolically written down by substituting zero for two line currents in the foregoing equation. If the relay impedance is negligible, then an earth fault current in line B will produce a corresponding current in the relay; when the fault current is in line A or line C the relay current will correspond to $1/\sqrt{3}$ times this current

A different kind of negative sequence relay from the foregoing, developed by the same company, is illustrated by Fig. 124B. Here the relay carries three windings. One is energised by B phase current. The second is supplied from an auxiliary current transformer T, so designed with an air gap in its magnetic circuit that the output current from it into the relay leads 60 degrees in phase on the A phase current. These windings are so proportioned that, with a balanced load, their resultant effect is zero. With current unbalance, the resultant magnetic effect of these two windings plainly depends upon the negative sequence component. In order to give response to earth fault currents in C phase, a third winding is provided, which carries the residual current. This winding is generally so proportioned as to give more sensitive response to earth faults than to short circuit faults. Typical settings are 50 per cent. (fixed) for *negative sequence currents, corresponding to 85 per cent.* single phase current, and 20 to 100 per cent. (adjustable) for earth fault currents.



(a) (b)

Fig. 125—Tuned Relay

Tuned Relays.—In certain circumstances, which will be mentioned later, it is essential that the relays used in connection with an automatic protective system be so designed that they are responsive only to currents of normal frequency and are unaffected by high-frequency currents which appear in the secondary circuits of the protective transformers in abnormal conditions. The simplest relays of this class are those which are tuned mechanically to give the required selective response. A typical tuned relay is shown diagrammatically in Fig. 125 (a). It comprises a reed of magnetic material, free to vibrate in a coil carrying the operating current, and in the field of a permanent magnet. The frequency of the reed is equal to that of the supply. The reed will be set in vibration when currents of the normal frequency flow in the operating coil, but will be unaffected by high-frequency currents. The vibration of the reed releases a spring controlled member carrying the trip circuit bridging contact. A relay of this kind must be reset by hand after operation. The variation of the current required to operate the relay for small changes of frequency is shown in Fig. 125 (b), and from this curve it is seen that the sensitivity is practically constant for such frequency variations as are likely to occur even during fault conditions.

B.S. Requirements for Protective Relays.—The B.S. requirements for protective relays are contained in the British Standard Specification No. 142, 1927. The most important of these requirements are summarised hereunder.

The lowest standard setting of an over-current A.C. relay is between 80 and 150 per cent. of the rated full load current. The highest setting is twice the lowest setting for time-lag relays and three times the lowest setting for instantaneous relays. The standard time setting for definite time-lag relays is between 10 and 0·5 seconds if non-adjustable : if adjustable the maximum time setting is between 10 and 2 seconds, and the minimum either one-fifth of the maximum or 0·5 seconds, whichever is greater. The time-lag of inverse with definite minimum time-lag relays must be constant for currents over five times the setting value. The maximum VA for an induction relay is 20 ; other types are divided into three grades whose maximum VA are respectively 20, 3, and 0·15. The actual minimum current required to operate an over-current relay must not differ from the nominal value by more than 10 per cent. Instantaneous over-current relays must complete their operation within 0·15 seconds with a current equal to one and a half times the setting value. The limits of time error with a definite time-lag relay are 10 per cent. of the setting value, or 0·2 seconds, whichever is greater. Inverse time-lag relays must reset when the current in their windings falls to 70 per cent. of the setting value. The standard minimum settings of directional relays are between 10 and 100 per cent. of the rated current with rated voltage. The highest setting is not more than three times the lowest. The standard maximum VA consumptions of the current and voltage circuits of a non-compensated directional relay are respectively 2 and 15. For compensated relays the corresponding figures are 3 and 20. The actual minimum current required to operate a directional relay with normal voltage must not differ from the nominal value by more than 10 per cent. A compensated directional relay must operate with five times the normal current, when the voltage falls to five per cent. of its rated value. A directional relay must not operate with a current in a direction nominally opposite to that to which the relay is responsive, equal to 30 times the setting value, with the voltage at 5 per cent. of its rated value.

The trip circuit contacts of protective relays must be competent to close a circuit consuming 350 VA subject to the stipulation that the voltage shall not exceed 660, and the current shall not exceed 3A.

CHAPTER VI

THE PROTECTION OF ELECTRICAL MACHINERY

The Requirements of a Protective Scheme for Alternators.—In considering the fundamental requirements of an automatic protective system for a turbo-alternator, it must be borne in mind that a machine of this class is liable to be subjected to three classes of abnormal conditions. These three classes are comprised under the heads of failure of the prime mover, failure of the D.C. excitation supply, and failure of the insulation of the windings or of the connecting cables. With regard to insulation failures, moreover, it is necessary to recollect that an alternator, driven by a prime mover, is still in a position to supply current to a fault in its own windings, after it has been disconnected from the rest of the system. Protective apparatus for dealing with insulation failures must therefore be so designed as not only to disconnect the machine from the bus bars, but also to extinguish the magnetic flux as rapidly as possible. Protective apparatus for turbo-alternators, therefore, invariably includes some appliance, usually designated field suppression gear, which interrupts the supply of direct current to the rotor on the appearance of an insulation failure in the main stator circuit.

A turbo-alternator, unlike most other types of electrical machinery, is usually under the direct and continuous supervision of a highly-skilled switchman or control engineer, and, for this reason, it is not usually considered necessary or even desirable to complicate the protective gear by providing for automatic disconnection in the case of a prolonged overload. Such an emergency is best dealt with by hand switching by the control engineer. Long time-lag protection against overloads of short-circuit magnitude is often provided, to disconnect the alternator in the event of the failure of the protective gear associated with an out-going circuit which is faulty.

Prime Mover Faults and Field Failures.—A failure of the steam supply to the prime mover of an alternator does not give rise to a condition of urgency which needs protective apparatus. If such a failure occurs the machine ceases to deliver load current to the bus bars, and draws a motoring current which is but a small fraction of the rated full load current. As the alternator remains in synchronism, there is no point in disconnecting it automatically when the supply of mechanical power fails. If the steam supply can be gradually restored, the alternator will pick up its load without disturbance. If the failure of mechanical power is permanent, the alternator is best disconnected by hand.

The electrical conditions arising out of a mechanical fault in the prime mover are so uncertain that it is usually considered best to deal with this emergency by hand switching.

The conditions which arise when the direct current exciting supply to an alternator fails have, in the past, been very generally misunderstood, and, even in recent articles and books, statements will be found to the effect that a field failure results in the alternator drawing load current from the bus bars The incorrectness of this view will be realised at once by recollecting that a failure of the field current does not directly affect the supply of steam to the prime mover, which supply is regulated by the governor at a value corresponding to the speed of the set. The alternator could only draw power current from the bus bars if its speed rose to such a value as to cause the governor completely to shut off the steam supply. Actually, when the field supply to an alternator fails, and this machine is connected in parallel with other machines to the same bus bars, the conditions which arise depend upon the load and excitation of the machine just before the failure occurs. If the machine is carrying a light load, and the other machines are working with strong fields, the faulty machine may remain in synchronism, continuing to deliver the same load as before the fault, but at a low leading power factor. The abnormal power factor is, of course, due to the fact that the exciting current of the faulty machine is carried by the stator, instead of the rotor, and is derived, not from the exciter, as normally, but from the bus bars. If the load on the faulty set is considerable, it will probably fall out of synchronism. Its speed will immediately tend to rise since it ceases to deliver load as a synchronous machine, but this rise in speed will result in a slip between the rotor and the rotating field set up by the reactive currents in the stator. Currents, at slip frequency, will thus be induced in the closed circuits of the rotor, and these, transferred inductively to the stator, will result in the machine continuing to supply power to the system. The tendency for the speed to rise is, therefore, checked, and the machine continues to supply a small amount of power, as an induction generator, the power factor, as before, having a low value and being leading.

A failure of the supply of the exciting current of a running generator does not, therefore, give rise to a power reversal, but the extra reactive load thereby thrown on the system tends to bring about a fall in the bus bar voltage, which may be serious if the rating of the faulty generator is of the same order as that of the remainder of the plant operating in parallel. If the field failure does not cause a serious fall in voltage, there is no occasion for the faulty generator to be disconnected automatically as the machine will re-synchronise and take up load again if the exciting current can be restored gradually. If, however, the fall in voltage is excessive, and the stability of the system is endangered, it may be advisable to disconnect the faulty machine automatically and so relieve the rest of the plant of the reactive load imposed by the faulty machine.

An ordinary reverse power relay is not competent to disconnect a generator whose exciting current supply has failed because, as we have seen, the direction of power flow does not alter. A directional relay compensated to be responsive to currents of low leading power factor can be used to deal with a field failure. The connections of such a relay are shown in Fig. 126, from which it will be seen that when the power factor is unity, the relay current leads in phase on the relay voltage by 30 degrees. If the power factor of the circuit in which the relay is connected falls below 0·5 leading, the effective lead of the relay current on the relay voltage will exceed 90 degrees, and the relay will tend to operate. Directional relays connected in this manner are not often used, as they are liable to be operated by the heavy cross-currents which flow between an incoming alternator and those which have been carrying load, when the incoming machine has been inaccurately synchronised.

A field failure of an alternator is best dealt with by means of a low-current relay in the rotor circuit. The exciting current of an alternator on open circuit, normal voltage, is of the order of one-half of the value corresponding to full load. There is thus an ample margin, within which a direct current relay can be set. Such a relay might well be interlocked with a low voltage relay responding to the bus bar pressure, in such a manner that a machine whose field current had failed would only be switched out if the bus bar pressure fell to a critical value. Relays arranged on these lines would be connected as shown in Fig. 127.

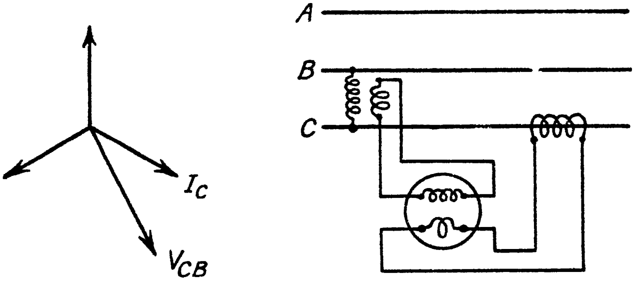


FIG 126—DIRECTIONAL RELAY TO OPERATE WITH FIELD FAILURE.

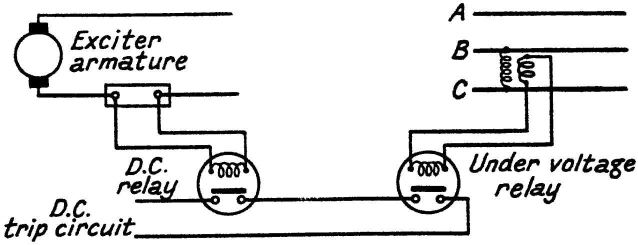


FIG. 127—RELAY COMBINATION TO OPERATE WITH FIELD FAILURE AND LOW VOLTAGE.

Field failures of modern alternators are comparatively rare occurrences, and as they do not involve the possibility of the destruction of plant, the trend of modern practice is not to install protective apparatus to deal with such failures automatically.

Insulation Failures.—Insulation failures constitute the class of fault for which automatic protective gear is most urgently required. Such faults involve the possibility of serious damage to expensive machinery, and it is in the highest degree necessary that immediately such a fault occurs, the alternator is disconnected from the system into which it is supplying, and also that it is rendered impotent to bring about its destruction by feeding current into its own fault. The fault current which will flow in an earth fault on a star-connected machine whose neutral point is earthed will evidently depend upon the distance between the fault and the earthed point, being a maximum near the line terminals and decreasing to zero at points adjacent to the neutral terminals. If a faulty machine has its star point free, and is operating in parallel with one whose star point is earthed, there will, due to third harmonics in the phase voltages, be a constant potential difference between the free star point and earth, and current will flow in an earth fault located at a point adjacent to the free star point. Generally, however, it may be said that with star-connected machines, the current flowing in an earth fault varies from practically zero to the value corresponding to that which flows in a dead earth on the bus bars into which the machines feed. It is, therefore, evident that it is impossible for automatic protective gear to be responsive to all faults which may occur on the stator of a star-connected alternator, but it must be remembered that, as the character of the insulation of the stator conductors of such a machine is uniform throughout the circuit, the possibility of an earth fault diminishes as the neutral point is approached.

Reverse Power Protection.—If an earth fault occurs on the stator windings of a star-connected alternator whose star point is earthed, the power flow from the machine to the bus bars in the earthed phase will tend to reverse if the power absorbed in the fault is approximately equal to that which the machine was delivering before the fault occurs. If the neutral of the machine is free, then fault current will be supplied from the earthed machines on load and, the direction of this fault current being opposite to that of the load current, there will be a tendency for the net power delivered by the faulty phase to reverse. Reverse power relays were the earliest used for the protection of alternators against insulation failures. The efficacy of these relays is very poor, as they are impotent until the magnitude of the fault current is greater than the load current, and if, as is not unusual, the maximum earth fault current is limited by the earthing resistance to a value approximately equal to the rated full load current of the alternator, no reversal of power will take place unless the fault is located in the windings very near to the phase terminals. The development of other and more sensitive schemes of protection has led to the supersession of reverse power relays for generator protection.

Where reverse relays are used, these are usually of the polyphase type, comprising two wattmeter elements, and responsive to the total power output of the associated machine. Three single-phase relay elements can be used, and these can be of the compensated pattern already described. The action of directional relays for generator protection is complicated by the fall in voltage which may take place if the magnitude of the earth fault current is considerable. In view of the fact that the use of directional relays for generator protection is becoming obsolete, this matter is mainly of academic interest.

Self-Balance Protection.—All modern systems for the protection of alternators depend upon the fact, studied in detail in Chapter III, that the criterion which indicates the presence of an earth fault in a conductor carrying current without tappings, is a difference between the current entering one end and that leaving the other end of the conductor. The technical problem involved in the application of this principle is that of the comparison of the two currents in the two ends of each phase of the stator winding. The simplest type of differential protection based upon the above principle is that associated with the names of Merz and Beard. This system is illustrated diagrammatically in Fig. 128, one phase only being shown. From the diagram it will be seen that the cables from the two ends of each stator winding are taken in opposite directions through the core aperture of a current transformer. The secondary current of this transformer is, apart from errors, proportional to the difference between the currents in the two conductors, that is, to the fault current. It will be understood that, for a given size of core and number of secondary turns, the secondary current for a given fault current is independent of the rated full load current of the machine. Fault current settings as low as 20 amperes can be readily obtained with the self-balance method of protection and, as the relay current depends upon the difference of primary currents, there is practically no tendency for the setting up of secondary currents when the machine is supplying external fault currents, however large these may be, provided the main cables are located centrally in the transformer core aperture.

When the fault current setting is under 50A, this value of this setting will represent the effective primary ampere turns of the protective transformer. As the core of this transformer must have an aperture large enough to accommodate two or four cables, the ratio of transformation with the current corresponding to the relay setting will be much larger than the turns ratio. A study of the discussion on p. 29 will make it clear that with the self-balance protection, relays having a low volt-ampere consumption at the setting current must be used if sensitive protection in terms of fault current is required.

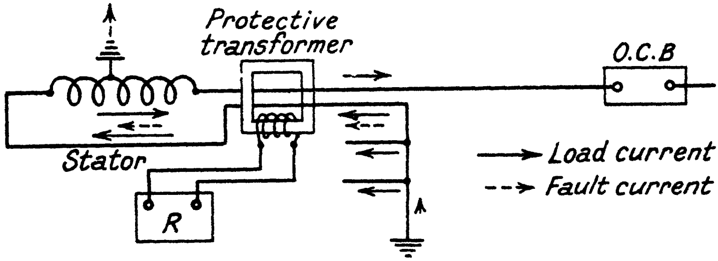


FIG. 128.—SELF-BALANCE PROTECTION FOR ONE PHASE OF A THREE-PHASE ALTERNATOR

It will be seen, from a study of Fig. 128, that the protective transformer constitutes the limits of the circuit protected, and that an earth fault on the conductors on the side of the transformer remote from the alternator will lead to no effective primary current in the transformer. In order, therefore, that the cables from the phase terminals of the alternator may be protected throughout by the self-balance scheme, it is necessary to extend the neutral connections of the stator windings from the machine to the switch unit. The cost of this procedure is prohibitive with large machines and, in view of the great reliability of single-core cables when these are carefully installed, it is usual to mount the protective transformers for the self-balance scheme, on the foundation block of the alternator and to dispense with automatic protection for the cables between the machine and the switch unit. These cables can, however, readily be protected by the scheme shown in Fig. 129, if they can be so installed that the sheaths are lightly insulated from earth throughout their length, and at their entry into the switch unit. From this diagram it will be seen that a current transformer is included in the cable bonding the sheaths to earth, and a relay is connected to the secondary winding of this transformer. If the insulation of the main cables breaks down, the greater part of the fault current will pass through the core of the current transformer, thereby energising the relay and tripping the oil circuit-breaker. As the fault current due to a breakdown of cable insulation will be considerable, the setting of the cable sheath relay need not be sensitive.

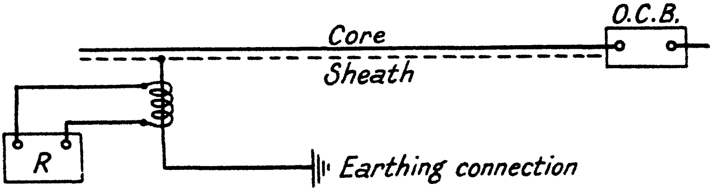


Fig. 129.—Cable Sheath Protection.

The self-balance protective system fails to respond to short-circuit faults between turns in the same stator circuit, since such a fault leads to no inequality between the currents in the two ends of the winding. When each phase of the stator comprises two parallel circuits the self-balance method can be used to give protection against this class of fault in the manner shown in Fig 130. The short-circuited turns cause a difference in the currents in the primary of the protective transformer, and this difference current induces a current in the relay connected to the secondary winding.

Merz-Price Protection.—The protective scheme associated with the names of Merz and Price differs from the self-balance system in that the secondary currents of current transformers connected at the two ends of the stator winding are compared by being superimposed on a relay circuit in the manner which has been dealt with in detail in Chapter III. It was there explained that, for the stability of this system of protection, it is highly important that the burdens on each of the pair of current transformers should be as nearly as possible the same. When the alternator is located at some distance from the switchgear the connection of the relay to the pilots carrying the secondary circulating current will most conveniently be made at a point nearer the bus bar transformer than that at the neutral point of the alternator. When this is the case, resistance is inserted in the main pilot wire on the side of the relay tapping towards the bus bar transformer, so that this relay tapping divides the whole secondary impedance of the two transformers into two equal portions

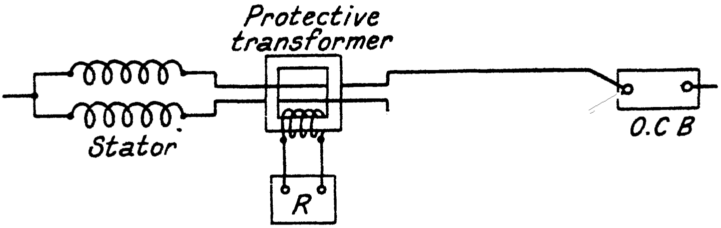


FIG. 130.—PROTECTION AGAINST FAULTS BETWEEN TURNS BY SELF BALANCE OF PARALLEL CIRCUITS

The connections shown in Fig. 131 are sometimes used. Here two relays and a balancing impedance are connected in star, and the third relay is connected between this star point and the fourth wire of the secondary circulating current circuit. The star-connected circuit being symmetrical as regards impedance, any symmetrical stray currents in this circuit will cancel at the star point and will not appear in the third relay The two relays R_1 and R_2 will be responsive to short-circuit faults between any pair of phases, while the relay R_3 will respond to earth faults. Due to the fact that symmetrical stray currents do not appear in R_3, it will be inherently more stable with straight-through short-circuit currents than relays R_1 and R_2, and its setting can be safely made lower than the two relays which are intended to deal with short-circuit faults.

It has already been explained that to obtain the maximum sensitivity of the differential protective system under consideration, the impedances of the relays must be correctly adjusted to a value depending upon the characteristics of the current transformers and upon the total burden imposed upon them by the protective circuit. With a properly designed circuit, arranged as Fig. 131, a setting of 10 per cent. of the rated full load current of the current transformers can be obtained. A low setting for the short-circuit relays is not very essential, and the setting of these relays may be of the order of 20 per cent. These settings, it should be observed, refer to the actual primary fault current required to operate the relays.

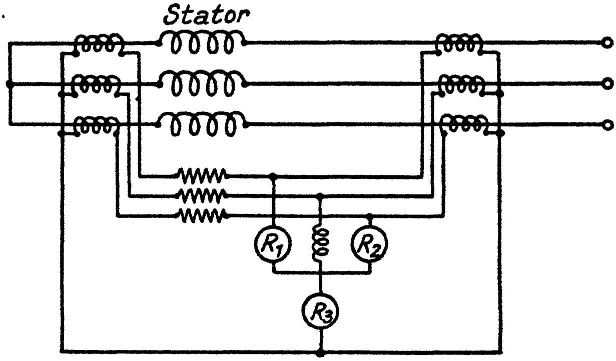


FIG 131.—MERZ-PRICE PROTECTION WITH EARTH LEAKAGE RELAY.

Due to the interconnection of the current transformers, and to the considerable burden imposed by the relay impedance to unbalanced secondary current, the relay settings in terms of secondary current will be considerably lower than in terms of primary fault current.

It must be noted carefully that the maximum practicable sensitivity of a Merz-Price protective system is expressed as a percentage of the rated full load secondary current of the protective transformers. The actual fault current required to operate the relay, therefore, depends upon the ratio of the protective transformers, and the sensitivity in terms of fault current will diminish as the rated full load current of the main primary current increases.

When the alternator stator circuits are duplicated, protection against short-circuited turns can be obtained, as with the self-balance system, by comparing the secondary currents of two transformers whose primary circuits carry the currents in the two circuits of the phase winding. The circuit for this protection is shown for one phase only in Fig. 132. Current will appear in the relay when the normal balance of the currents of the two circuits is disturbed by short-circuited turns.

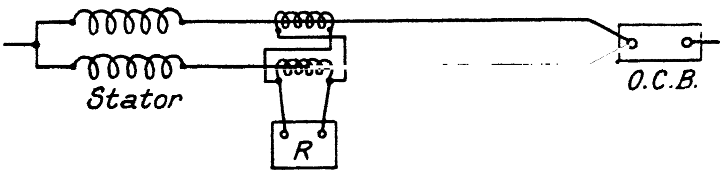


Fig. 132.—Differential Protection against Faults Between Turns.

Biased Systems of Differential Protection.—The principle of biasing as applied to differential systems of protection of the Merz-Price class has been considered in detail in Chapter V. The application of the biasing principle by the use of biasing transformers, beam relays, or double-circuit induction relays, described on pp. 165 to 172, to generator protection is easily understood and needs no further explanation, as the secondary protective circuit for a three-phase circuit is simply a combination of three single-phase circuits with a common return.

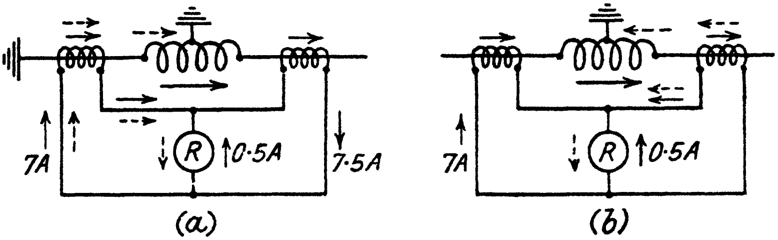


Fig. 133.—Biased Differential and Reverse Power Protection.

A further scheme of biased differential protection which has been applied to generators is illustrated by Fig. 133. In this circuit the ratios of the current transformers at the two ends of each stator winding are slightly different, the full rated current of the neutral point transformers being 7A and that of the bus bar transformers being 7·5A. A current corresponding to about seven per cent. of the load current is thus permanently diverted into the relay in the difference circuit. This relay is of the compensated directional type, and the polarity of the voltage winding is such that this permanent difference current holds the trip circuit contacts open. Fig. 133 (a) shows the conditions for an internal fault when the neutral of the machine is earthed, and it is clear that when the magnitude of this current exceeds seven per cent. of the load current, the direction of the current in the relay reverses and a tendency to operate is set up. When the neutral of the faulty machine is free, the conditions are as shown in Fig. 133 (b). The fault current is now fed from the bus bars, and is superimposed in a reverse direction on the load current. The magnitude of the current in the bus bar transformer is thus reduced, and when the current in the fault has a value corresponding to seven per cent. of the load current the direction of the relay current will be reversed.

As the magnitude of the fault current required to cause reversal of the relay current is expressed as a constant ratio of the load current, the system is biased, and its sensitivity decreases as the load current increases. A reversal of the direction of power flow in the alternator will also reverse the direction of the currents in the relays. The system, therefore, gives reverse power protection.

Earth Fault Protection.—If it is considered sufficient to provide protection against earth faults only, a simple leakage protective circuit will meet this requirement. As an alternator, if star-connected, may be run with an earthed neutral, the alternator must be treated as a four-wire circuit, the fourth wire being the connection of the neutral point to earth. Fig. 134 shows the connections of the leakage protective circuit in which the relay carries the resultant of the secondary currents of four current transformers, one of which is connected in the cable, which earths the neutral point of the machine. When the alternator is supplying current to an external earth fault, the secondary current of the transformer in the earth connection will be cancelled by a corresponding current in one of the transformers in the main connections and no current will appear in the relay. When the earth fault is in the machine winding itself, the current from the transformer in the earth connection will not be cancelled, but will appear in the relay. If the neutral of the machine is free, then current will evidently be fed into the fault from the bus bars, and the relay current will correspond to the fault current which is superimposed on the load current.

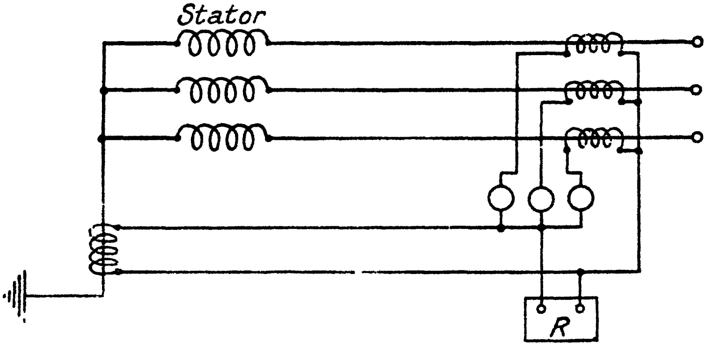


FIG. 134.—EARTH FAULT PROTECTION OF A THREE-PHASE ALTERNATOR.

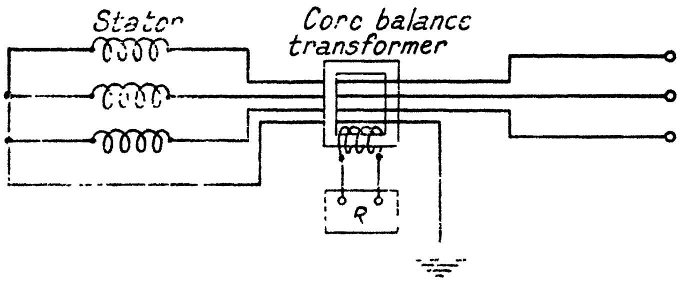


FIG. 135.—EARTH FAULT PROTECTION BY CORE-BALANCE TRANSFORMER

An alternative scheme for leakage protection of an alternator is shown in Fig. 135. Here the three main cables, together with the neutral earthing connection, are taken through the core aperture of a current transformer. This circuit is the equivalent of Fig. 134, in that the relay current is representative of the resultant of the currents in the four primary conductors.

Protection against Faults between Turns.—The schemes of protection described above are only suitable for dealing with faults between turns when the alternator is wound with duplicate circuits. A scheme for dealing with this class of fault in alternators with single circuits is shown in Fig. 136. Here a mid-point tap on each stator winding is joined, through the primary of an isolating transformer to a mid-point tap in the winding of a choke coil or voltage transformer connected in parallel with the stator winding. The two taps are normally at the same potential, and no current appears in the relay connected to the secondary winding of the isolating transformer. A short-circuit between turns of the stator winding disturbs the voltage balance, and current passes in the cross-connection, and this is transferred inductively into the relay circuit.

The disadvantage of this scheme is that three extra conductors at high potential have to be taken from the alternator to the switchgear. The difficulties of dealing with these additional connections are much greater with armour-clad than with cellular switchgear, and it is probably due, in a large measure, to the standardisation of the armour-clad type of gear, that this system of protection against faults between turns has not been adopted. The protective systems of modern alternators of moderate size, with single circuits, do not include any feature for dealing with faults of this type.

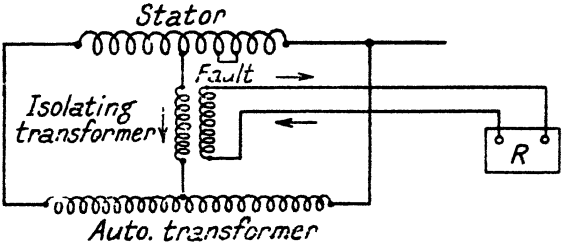


FIG. 136.—PROTECTION AGAINST SHORT-CIRCUITS BETWEEN TURNS

Field Suppression Gear.—We have already referred to the fact that the protective relays for a turbo-alternator must, in addition to disconnecting a faulty machine from the bus bars, operate some device for interrupting the supply of direct current to the rotor windings. This device can be operated simultaneously with the tripping of the oil circuit-breaker, or immediately after such tripping. As it is not practicable to have the operating coil of the field suppressor switch connected permanently in parallel with the circuit-breaker trip coil, an auxiliary relay with three contacts, connected as shown in Fig. 137 (a), is used if simultaneous operation of the suppressor and the oil circuit-breaker is required. The operation of the protective relay energises the auxiliary relay which, in turn, simultaneously energises the operating coil of the suppressor switch and the trip coil of the oil circuit-breaker. A push-button switch is often connected in parallel with the switch of the protective relay for emergency use. The normal operation of the circuit-breaker controller, of course, merely trips the breaker and does not affect the field circuit. The alternative method of controlling the field suppressor is shown in Fig: 137 (b) In this case the suppressor is energised, after the operation of the protective relay, by special auxiliary switch on the main oil circuit-breaker, which makes contact after the breaker has tripped. The advantage of the latter system is that the field current cannot be interrupted while the alternator is still connected to the bus bars, but, in point of practical utility, there is little to choose between the two schemes.

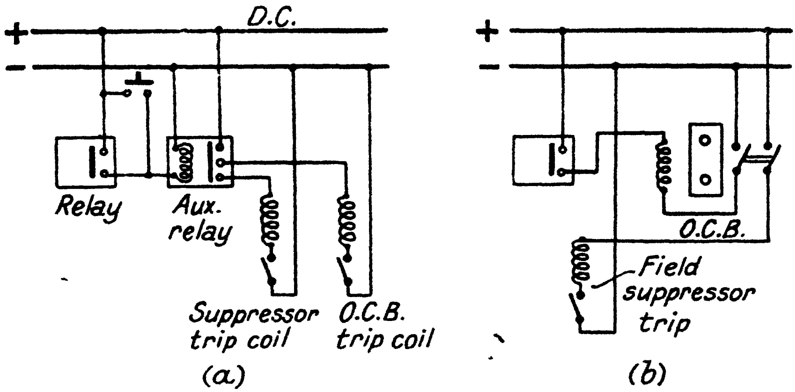


Fig 137.—Operating Connections of Field Suppression Gear

The usual arrangement for suppressing the field of an alternator is shown in Fig. 138. The suppressor switch takes the form of a D.C. circuit-breaker with an extra blade which, when the connection of the exciter to the rotor is broken, joins in parallel with the rotor, a non-inductive resistance. The closing of the rotor circuit through the resistance limits the rise of pressure due to the opening of the normal circuit, and this limitation of pressure rise is also assisted by the eddy currents in the rotor body which behaves as a discharge resistance which is inductively coupled with the rotor circuit. Limitation of the pressure rise is, however, obtained at the expense of rapidity of suppression of the magnetic field, and the smaller the pressure rise, the longer the field takes to vanish. In some cases the discharge resistance is omitted altogether, in order to secure rapid field suppression. When this method is used the rise of pressure in the rotor circuit is considerable, in spite of the modifying effect of the eddy currents in the rotor core.

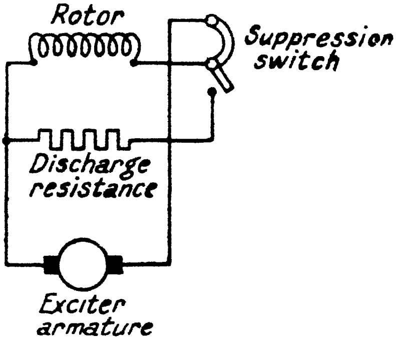


FIG. 138.—CONNECTIONS OF FIELD SUPPRESSION GEAR.

It is now generally recognised that undue importance was, till recently, ascribed to rapid suppression of the alternator field by the agency of the protective apparatus. Oscillograph tests, with the alternator on open circuit, show that, unless the rotor circuit is broken completely, an appreciable field persists for some seconds after the operation of the field suppression device. The circumstances are considerably modified when the suppressor is operated by the protective relays on the occurrence of a fault in the alternator windings, as the fault currents flowing in these windings have a demagnetising effect on the rotor which rapidly extinguishes the flux. In fact, Continental practice at the present time favours the use of a suppression switch in the exciter field, on the ground that in this position the necessity of a heavy current carrying automatic device in the main rotor circuit is desirably avoided.

Standby Protection for Alternators.—*The foregoing paragraphs deal with protective apparatus designed to disconnect an alternator on the occurrence of internal faults. It is usual to install some additional protective device in the con*trol gear of large alternators which will disconnect the machine if, due to the failure of external relays, it is required to supply current to a line fault for an inordinate time. This additional device may be an over-current relay with high current and time settings. A better type of relay to deal with conditions of sustained external faults is one uniquely responsive to negative and zero sequence components in the alternator output. With modern transmission systems there is a possibility that fault currents, sustained because of the failure of a network relay, may be quite moderate in magnitude, and incompetent to operate a generator over-current relay with a safely high current setting. The sustained flow of fault current in an alternator winding is, however, dangerous. The armature flux set up by the negative and zero sequence components in this current does not rotate synchronously with the rotor, and induces therein eddy currents in local circuits which give rise to dangerous abnormal heating. A relay responsive to negative and zero sequence currents will disconnect the machine in such a condition, even though the total output of the alternator is relatively moderate. Such a relay is described on p. 171 and it is generally used in conjunction with an auxiliary timing relay having a setting adjustable between 0 and 10 seconds. A representative setting of the negative sequence relay corresponds to a 40 per cent. single phase current between lines. If desired, the negative sequence relay can be supplemented by a single over-current relay, also controlled by the auxiliary timing relay, and having a setting of the order of 200 per cent. This will deal with conditions of sustained balanced overload.

Alternators generating at a pressure of 33KV have occasionally failed due to flash-over resulting from excessive pressures to earth, and these failures are suspected to be due to the phenomenon of neutral inversion, described on page 66, because they have occurred during the periods that the machines with unearthed neutrals, have been disconnected from the bus bars preparatory to or after carrying load. It should be noted that with alternators of this type, single-phase voltage transformers with primaries connected in star, are essential in order to obtain phase-isolation in the switchgear and to avoid the expense and complication of an insulated conductor passing from one transformer to the others. It has been proposed to obtain automatic protection against this kind of failure by providing the voltage transformers with tertiary windings connected through a loading resistance, in delta, and to join to this resistance an over-voltage relay controlling the field-suppressor of the machine, so that in the event of unstable conditions giving an excessive residual voltage, the field of the machine will be suppressed and the overpressure tendency checked.

General Requirements for Transformer Protection.—If the secondary circuit of a transformer is isolated, protection against internal faults in either the primary or secondary windings can be obtained by the use of over-current relays controlling the supply to the primary, a time-lag being provided in these relays, if thought desirable to allow of the disconnection of faulty secondary circuits before the primary supply is interrupted. Such a scheme will, evidently, be unsuitable for transformers which are connected in parallel on the secondary side, as power will be supplied, through all the transformers, into a fault on any one of them, and all the transformers will ultimately be disconnected on the primary side. The use of directional relays, controlling the connections of the secondary windings of the transformers to the secondary bus bars, would be one method whereby one transformer of a bank could be disconnected in the event of a fault in either its primary or secondary windings, the remaining transformers of the bank carrying the power supply from the primary to the secondary system. Directional relays are not, however, used for transformer protection, and, with one exception, all systems of protection for transformers operating in parallel are of the differential type and depend, essentially, upon the comparison of currents in the primary and secondary circuits which are either equal or which bear an approximately fixed ratio in normal conditions.

Tank Earth Protection.—This system, which constitutes the exception referred to in the preceding section, consists in the control of the breakers on the primary and secondary sides of the transformer by a relay which is responsive to currents in the earthing connection of the tank of the transformer. The connections are shown schematically in Fig. 139, and from this diagram it will be seen that, provided both the primary and secondary systems are earthed, a breakdown of the insulation from conductor to core will result in the flow of a current in the conductor earthing the tank, which current, through the agency of a current transformer, will operate the protective relay and disconnect the transformer. The tank earth system of transformer protection is very simple, and provided certain precautions are taken, is very effective in affording sensitive protection against the majority of failures to which transformers

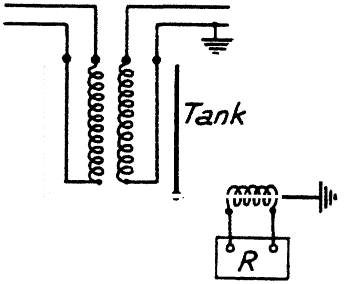


Fig 139—Tank Earth Protection for Power Transformers

are liable. To give successful results it is, first, essential that the flow of fault current be restricted to the earthing connection of the transformer in which the breakdown occurs, and, secondly, that precautions be taken that there is no possibility of even a small fraction of this current finding its way into the tank earthing connections of other transformers of the bank To ensure that practically the whole of the current in a transformer fault flows in the tank earth, it is evident that the tank must be lightly insulated from earth when this connection is broken. There must, therefore, be no electrical continuity between the tank and the cable sheaths associated with the transformer. If the transformer is mounted on rollers and stands on a concrete floor, the resistance between the tank and earth, with the cable sheaths so isolated and the earthing connection broken, will be sufficient to divert practically all the current due to a fault into this connection. Great care must be taken to avoid any direct metallic connections between the several tanks of the transformers of a bank, and if temperature alarms are fitted, the electrical circuits for all the transformers must be kept separate and mutually insulated. Due to the necessity of the electrical isolation of the tanks of all the transformers of a bank, the tank earth system of protection is most suitable for oil-immersed, self-cooled machines of moderate rating. If forced cooling by oil or water circulation is used, the electrical isolation of the several tanks will be obtained with difficulty, and other methods of protection will be found more suitable.

The tank earth system of protection is responsive to faults caused by failures of insulation from conductor to core, but not to those due to short-circuited turns or to short-circuits between phases. As current can only appear in the earthing connection on the occurrence of an insulation failure, the method is not subject to transient disturbances during switching in conditions such as will be dealt with later, and the setting of the relay can safely be given such a value as to give very sensitive protection. One relay, and one current transformer only, are required for each power transformer. The trip circuit contacts of this relay will be connected so as to energise the trip coils of the breakers on both primary and secondary sides of the transformer simultaneously.

Self-Balance Protection.—The application to power transformers of the self-balance system, already described in reference to alternators, gives very complete and efficient protection against earth faults and short-circuits between phases, but not against short-circuited turns. The disposition of the self-balance protective current transformers for a delta-star power transformer is shown in Fig. 140, the secondary windings of these protective transformers being omitted, and the application of the method to other types of three-phase transformers will need no explanation. The protective transformers may be placed in the transformer tank, under oil level, but this arrangement, although giving a convenient and compact assembly, does not give protection to the terminals of the main transformer. If the protective transformers are installed externally to the transformer, the interconnection of the primary and secondary windings of a three-phase transformer must be made externally and this arrangement is very undesirable for transformers for use in situations where space is restricted. The self-balance system with the protective transformers inside the tank, used in conjunction with the tank earth system to give protection against terminal faults, would afford efficient and sensitive protection covering all failures but those due to short-circuited turns.

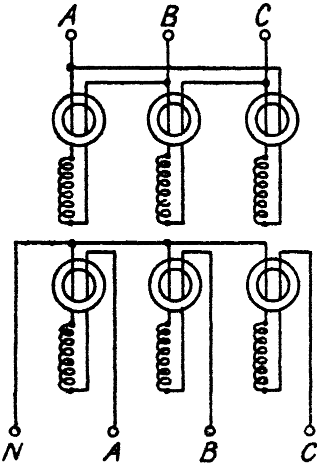


FIG 140.—SELF-BALANCE PROTECTION OF A THREE-PHASE TRANSFORMER

Merz-Price Protection.—The application of the Merz-Price current balance system of protection is not quite straightforward in its application to power transformers as to generators, since the currents in corresponding primary and secondary conductors of a transformer are not normally equal. It is, however, a simple matter to arrange that the ratios of the protective current transformers on the primary and secondary sides of the transformer are such that load currents give rise to equal currents in the secondary windings of the protective transformers. These secondary circuits can now be interconnected in the manner discussed on p. 70, and the protective relay will then be responsive to differences in the secondary currents of the protective transformers which are set up by faults in the main power transformer.

Even when the ratios of the protective transformers are proportioned in this way, there arise further difficulties in the application of the Merz-Price system to power transformers. In the first place, the exciting current which flows in the primary circuit is not transferred inductively to the secondary circuit, and this component of the total primary current gives rise to an unbalance of the secondary currents of the protective transformers, which appears permanently in the protective relay. In normal circumstances this permanent out-of-balance current is only of the order of five per cent. of the rated full load current of the transformers, and by setting the relay to respond to a current in excess of this permanent out-of-balance, the disadvantage of the unbalancing caused by the exciting current might be considered to be avoided. When, however, a dead transformer is switched on to the supply, the exciting current may assume a very high value. Suppose, for instance, the voltage of the supply is applied to the transformer windings at the instant of its zero value. Now the change in the magnetic flux in the core during a half-cycle of voltage change from zero to zero is from a positive maximum to a positive minimum, the total change in the flux being twice its normal maximum value. If the unmagnetised core is energised at a zero value of the voltage, the total change in the flux for the first half-cycle of voltage must still be about equal to double the normal maximum value, and accordingly, during this first half-cycle, the flux rises to this double value. Due to the fact that the normal maximum value of the flux is very near the saturation value, the value of the exciting current required to produce the abnormal flux density during the first half-cycle will generally be in excess of the full load current of the transformer, and a high current, corresponding to this abnormal exciting current, will appear in the relay of the Merz-Price protective circuit. The abnormal value of the exciting current only persists through a few cycles, and the normal value is rapidly attained. If the voltage is applied to the windings of the transformer at a point of maximum value, there will be no abnormal rush of exciting current. Generally, the transient value of this current depends upon the phase of the voltage at the instant of switching-in and also to some extent upon any residual magnetism in the core, but the possibility of a transient value of the exciting current of the order of full load current, when switching-in a power transformer, is quite considerable. Similar, but smaller, transient high values of the exciting current may occur if, due to system disturbances, the voltage applied to the transformer windings increases suddenly.

A second source of complication in the application of the Merz-Price system of protection arises when three-phase transformers with dissimilar interconnection of the primary and secondary windings are concerned. With such transformers the currents in corresponding external conductors connected to the primary and secondary windings are not only unequal, but are not in phase, so that the equality of the secondary counterparts of these currents cannot be tested by superposition in a relay winding.

The most effective method of preventing operation of a relay used with a Merz-Price protective circuit by current rushes which occur at switching-in is by the use of one having a small but definite time-lag. The induction type of relay has the required characteristic, and, however great may be the rush of current, the time-lag will never diminish below a value which can be made sufficient to allow the primary current to subside to its normal magnitude. Another method is to use instantaneous relays of the attracted armature type shunted by time limit fuses. Unlike the induction relay, the fuse has a time-lag which diminishes indefinitely as the current through it increases and, to avoid melting of the fuse by the current rush which may occur in a most unfavourable phase of the voltage at the instant of switching-in, the limiting current the fuse will carry indefinitely must be given a value so high that the sensitivity of the protection is very low. The fuses can be withdrawn, when the transformer is switched in, but there will still remain a slight possibility of sufficient current appearing in the relay to cause operation if a sudden change in the voltage causes a transient increase in the exciting current. A good arrangement, if it is desired not to use induction relays, is to shunt the attracted armature relays by light time limit fuses and to provide a spring-off switch to short-circuit relay and fuse while the transformer is switched in. This arrangement, for a three-phase transformer, is shown in Fig. 141, and it has the disadvantage that at the instant of switching in the transformer is deprived of protection.

A difference in phase between primary and secondary currents of a three-phase transformer arises when the interconnection of the three transformer units is different on the primary and secondary sides Such a phase difference arises when a star connection on one side is associated with a delta or an interconnected star connection on the other. The amount

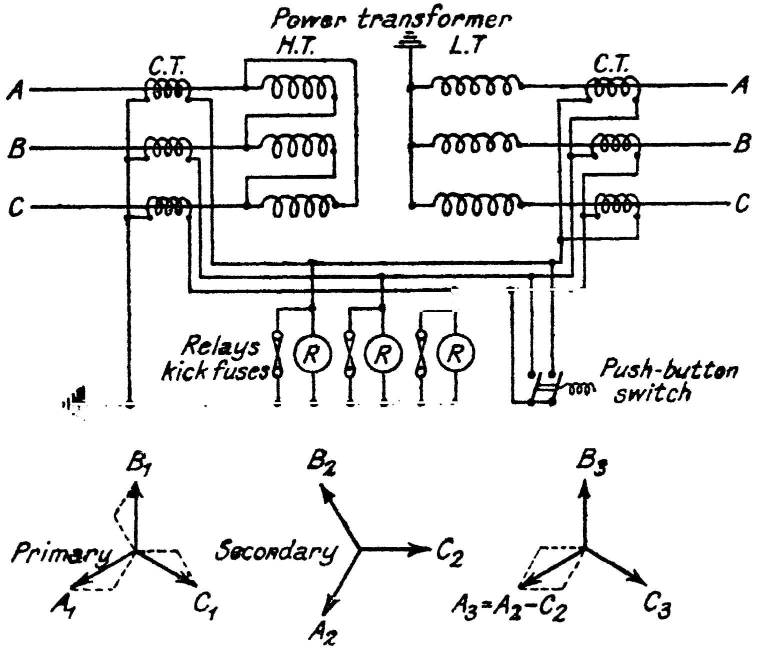
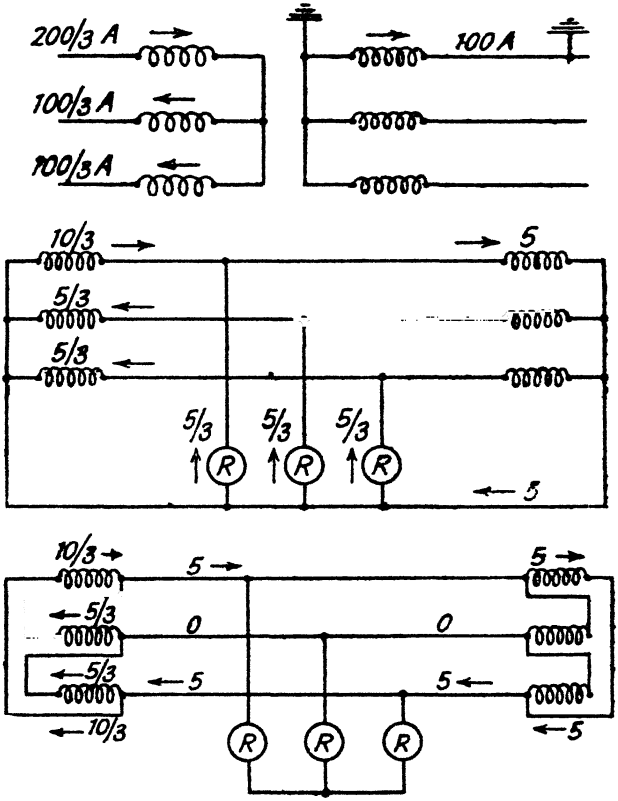


FIG 141 – MERZ PRICE PROTECTION FOR A DELTA STAR POWER TRANSFORMER

of this phase difference is 30 degrees ; and the interconnection of the protective transformers is so arranged that there is a compensating phase difference between the secondary currents of the two sets of protective transformers which annuls that due to the phase difference of the main currents. Thus, in a delta/star power transformer, the protective transformers on the primary side are connected in star, and those on the secondary side are connected in delta The arrangement is shown in Fig. 141.

When the interconnections of the primary and secondary windings of the power transformer are similar, those of the protective currents will likewise be the same, but care must be taken in choosing the system of interconnection of these protective transformers if one winding of the power transformer forms a circuit for zero phase sequence currents while the other forms an open circuit to them. If, in these circumstances, the protective transformers are star-connected with a common fourth wire return, an unbalanced zero sequence component will flow in the protective circuit when the power transformer carries a zero sequence current due to an earth fault external to the transformer. If, however, the protective transformers are delta-connected on both primary and secondary sides, the zero sequence current is suppressed in the delta and does not appear in the protective relays. This point is illustrated in Fig. 142, which shows the currents flowing in both windings of a star star power transformer with an earthed secondary neutral and an earth fault on the secondary side external to the transformer. The earth fault current is assumed to be 100A, and the ratio of the transformer is taken as unity The currents in the Merz-Price secondary circuits are also shown, first with a star and secondly with a delta connection of the protective transformers, a ratio of 100/5 being assumed. It is seen that, notwithstanding the power input to the main transformer is equal to its secondary power output, the currents in the secondary winding of the protective transformers do not balance when these transformers are star-connected. With the delta connection this unbalance disappears and only an earth fault in the secondary windings of the transformer will give rise to operation of the protective relays. This discussion indicates clearly that when either a primary or secondary star point of a power transformer is earthed, the Merz-Price protective transformers on the side having the earthed neutral must, in all cases, be delta-connected, otherwise operation of the protective relays may be caused by an earth fault external to the transformer. This point is of great importance and should be clearly grasped by the student.

Another difficulty which arises in the application of the Merz-Price system to transformer protection is due to the fact that it is rarely possible or desirable for the protective transformers on the primary and secondary sides to have equal numbers of ampere turns. On the high-pressure side it is generally desirable to use bar primary transformers and the ampere turns of these transformers will be quite small, while the ampere-



(*Top*) Main Circuit

(*Middle*) Secondary Connections of Star-connected Protective Transformers.

(*Bottom*) Secondary Connections of Delta-connected Protective Transformers.

Illustrating theory of the Merz-Price protection of a star star power transformer.

Fig. 142

turns of similar transformers on the secondary side will usually be sufficient to give good accuracy characteristics over a wide range of currents. The difficulties due to conditions of this kind have been dealt with in detail on p. 79 and the most important application of the B.T.H. protective circuit there described is for the protection of power transformers.

The final difficulty in the application of the Merz-Price system arises with power transformers having tap-changing apparatus. It is evident that one set of ratios of the protective transformers will suit only one position of the tap-changing switch, and that, for other positions of this switch, the ratio of the rated currents of the protective transformers will not correspond to the ratio of the power transformer, and that there will be an out-of-balance current in the protective circuit which appears in the relay, and which is the same percentage of the secondary full load current as the percentage deviation of the tapping in use from that giving normal ratio. This difficulty can be overcome by a tap-changing device varying the ratio of one of the sets of protective transformers in conformity with the variation of the ratio of the power transformer. Such a current transformer tap-changing switch would, however, be an undesirable complication in a transformer protective circuit, and is rarely used. If the variation in the power transformer ratio by tap-changing is small, the tendency of the out-of-balance current in the protective circuit to operate the relays can be negatived by the use of insensitive settings. It must, however, be remembered that the out-of-balance current, being due to incorrectness of transformer ratios, will, unlike that due to exciting current, increase proportionally to the load carried by the transformer, and will tend to make the protection unstable under conditions of short-circuit external to the transformer. The Merz-Price system is, therefore, inherently unsuitable for transformers with tap-changing apparatus, and the self-balance system already described, or the balanced earth leakage system dealt with hereunder, are more suitable.

Scott-connected transformers for conversion from three- to two-phase can be protected by the Merz-Price system by converting the secondary currents furnished by three current transformers on the three-phase side to a two-phase system corresponding to that given by the current transformers on the two-phase side. The interconnection for this conversion has been already explained on p. 70 and the complete diagram for a

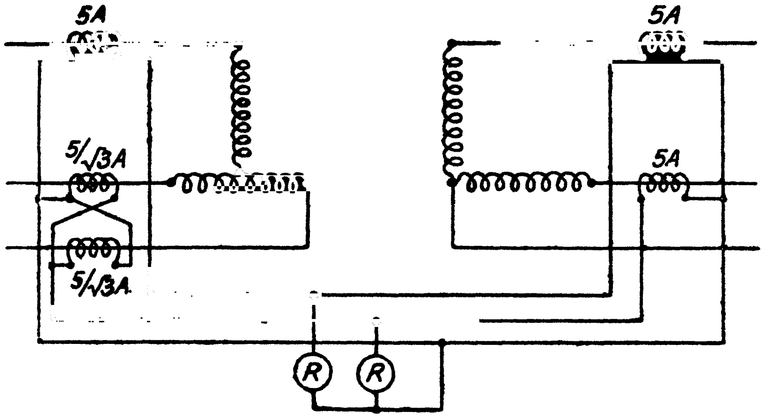


Fig. 143.—Merz-Price Protection for a Scott-connected Transformer Bank.

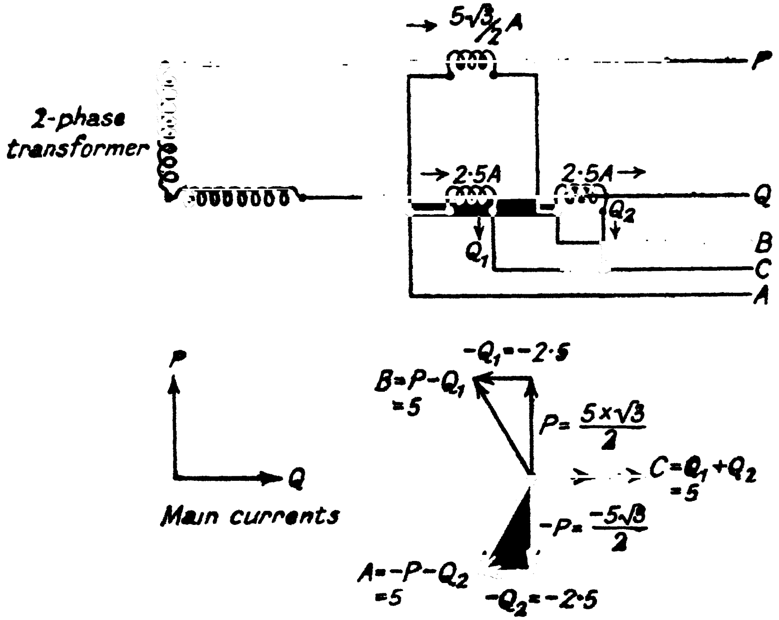


Fig. 144.—An Alternative Merz-Price Circuit for a Scott-connected Bank.

Scott-connected transformer is given in Fig. 143. Alternatively, it is possible to convert the two-phase system of secondary currents into a three-phase system as shown in the diagram, Fig. 144. This method, however, requires one transformer more than when a two-phase circulating current system is used, and it is rarely used.

Scott-connected transformers are generally used to convert from three-phase to two-phase. Occasionally the reverse transformation from two-phase to three-phase is used, in which case a neutral point for earthing can be obtained on the three-phase side by a 33 per cent. tap on the teaser transformer. In such a case the star connection of the protective transformers on the three-phase side would give rise to out-of-balance currents in the protective circuit with earth faults external to the transformer as described on p. 207. In such a case, therefore, the Merz-Price system would be unsuitable, and one of the other methods of protection would have to be used.

The application of the biasing principle to the Merz-Price system for protecting power transformers is exactly the same as to generator protection, and the various methods of biasing, by beam relays, by double-circuit induction relays, by directional relays, or by the use of a biasing transformer, which have been fully described are applicable equally to transformer protection as to generator protection.

Balanced Earth Leakage Protection.—This method of protecting power transformers is somewhat similar to that described on p. 193 for generators and is shown diagrammatically in Fig. 145. The primary side of the transformer, shown unearthed, is protected by an ordinary leakage relay circuit which has been described on p. 56. The secondary side of the transformer, the neutral of which is earthed, is protected similarly, but an additional current transformer is installed in the earthing connection. The ratio of this transformer is identical with that of the three transformers in the main secondary connections, and the secondary windings of all four current transformers are connected in parallel with the protective relay. Earth faults on the primary windings will operate the leakage relay on the primary side. Earth faults on the secondary windings will give rise to a current in the earthing connection, but not to a corresponding current in the main secondary connections, so that the secondary leakage relay will tend to operate.

A secondary earth fault, external to the power transformer, will give rise to equal currents in the earthing connection and in one of the main secondary connections. In these conditions the secondary leakage relay will be unaffected, as has been explained on p. 57.

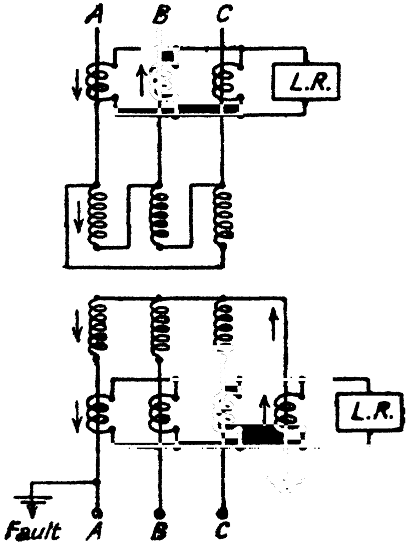


FIG. 145.—EARTH LEAKAGE PROTECTION FOR A THREE-PHASE TRANSFORMER.

The balanced earth leakage system of protection is only competent to deal with earth faults, and not with faults between phases or between turns. From the point of view of elementary theory, the primary leakage relay should be unaffected by current rushes on switching-in since it would appear that the primary circuit, being unearthed, could carry no residual current. Experience has proved, however, that a leakage relay in the primary of a large power transformer is liable to be operated by heavy transient currents on switching-in. The cause of this anomalous operation is obscure, but oscillograph records show that such transient currents have extraordinary wave forms, and it is probably to this that the relay instability must be attributed. Due to this instability it is advisable to use in the primary circuit a relay with an inverse time characteristic.

The stability of a leakage relay can also be improved by artificially increasing the impedance of the branch of the secondary network containing it, by added resistance. This will tend to decrease the relay sensitivity in terms of primary fault current, as explained in Chapter III.

In the event of the primary neutral of the power transformer being earthed, as well as the secondary neutral, then an additional current transformer would be provided in the primary neutral earthing connection, and the secondary winding of this transformer would be connected in parallel with those of the current transformers in the three main primary conductors.

Three-Winding Transformers. If the tertiary of a three-winding transformer consists only of a delta winding to provide a low-impedance path for the flow of earth fault currents in the secondary, and supplies no external load, no modifications are required to the ordinary Merz-Price protective circuit. The necessity for the delta connection of the protective transformers on both primary and secondary sides of a star star transformer has already been explained, and this necessity applies equally when the power transformer has an isolated delta tertiary winding. If, however, power is drawn from the delta tertiary, the problem of applying the Merz-Price method is somewhat difficult, since the combined output of the secondary and the tertiary circuits must be combined to balance the primary input. In such a case the self-balance, or the balanced earth leakage methods of protection, will be preferable since, with both of these methods, the several circuits in the power transformer are dealt with individually.

Protection Against Short-Circuited Turns.—The effect of short-circuited turns in either the primary or secondary winding of a power transformer is to alter the apparent ratio of transformation, since the primary ampere turns have to supply, not only the secondary ampere turns communicated to the external circuit, but also those corresponding to the current in the short-circuited turns. Due to the alteration in ratio effect, the Merz-Price protective system is not [illegible] responsive to faults arising from short-circuited turns. The relay settings used with this system are, however, necessarily insensitive and, unless the change in ratio due to the short-circuited turns is considerable, the resulting out-of-balance of the currents in the protective circuit will be insufficient to operate the relay. With transformers of normal design the Merz-Price protection is the only one available against this class of fault. When, however, each winding of the transformer can be divided into two sections, so disposed on the core that the mutual inductance of these sections is small, very sensitive protection against short-circuited turns can be obtained by a comparison of the currents in the two sections by means of a self-balance current transformer, as a fault of this nature will disturb the normal equality of these currents.

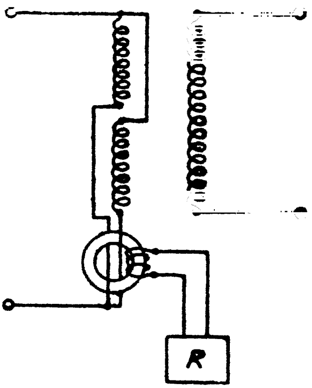


FIG. 146. PROTECTION AGAINST FAULTS BETWEEN TURNS

The connections of a single-phase transformer with a primary winding divided into two parallel sections and protected against short-circuited turns by the self-balance method are shown in Fig. 146.

Other Methods of Transformer Protection.—The Buchholz system of transformer protection depends upon the formation of bubbles in the oil of a transformer when a fault occurs. These bubbles set up currents in the oil which give rise to displacement of a pendulum or float device, the movement of which trips the oil circuit-breakers controlling the primary and secondary sides of the transformers. The Buchholz method is particularly suitable for transformers fitted with conservator tanks, as in this case the pendulum valve is conveniently located in the connection between the main and conservator tanks and gives a very sensitive response to a fault in its incipient stages.

In another recently developed system of transformer protection, the relay controlling the input and output circuit-breakers is responsive to the change in capacitance of an oil-immersed condenser, piped up to the transformer tank, caused by the entrapment of gas bubbles set up by an arc in the tank

When transformers are immersed in synthetic fireproof oil, a very simple, modern method of automatic protection depends upon the formation of a minute trace of hydrochloric acid by an arc in the oil, whereby the electrical conductivity of this oil is increased. A relay responsive to this conductivity can be made to disconnect the transformer immediately after the occurrence of an internal fault.

Standby Protection for Transformers.– In addition to the various differential methods of protection described above for power transformers, it is advisable and customary to install over-current relays on the primary side to operate in case of a failure of the differential protection. Over-current relays cannot give discriminating protection, and to avoid their operation except in fault conditions, it is advisable that the current settings be determined by the primary current which would flow with a short-circuit on the secondary bus bars. The thermal over-current capacity of an oil-immersed power transformer is so great that protection against .prolonged overloads is best given by thermal relays when such protection is required. When a transformer is under observation, the readings of a dial thermometer give the best indication of the manner in which the transformer is handling its load, and a high temperature alarm device incorporated in the thermometer, indicating when the overload capacity of the transformer has been nearly exhausted, is more convenient than an overload tripping device which disconnects the transformer without warning.

Bus-Bar Protection.—If a fault occurs on that portion of a main switchgear equipment supplying an isolated area which is situated electrically between the protective transformers of the generators and those of the outgoing circuits, no relays can be affected, other than those responsive to overloading or the delivery of negative or zero sequence currents by the generators. A fault in the bus-bar zone of a main switchgear equipment creates a very serious condition in that it gives rise to the possibility of extensive damage and prolonged interruption of the supply to consumers.

Notwithstanding that negative sequence protection of generators will probably be competent to deal with bus-bar faults, some engineers consider that, to avoid even the possibility of the disastrous effect of a dangerous fault, additional protective gear should be used which will completely disconnect a switchgear equipment from all sources of power. A simple method of achieving this result is similar to what has already been described as tank earth protection for transformers. The metallic armouring of the switchgear equipment is isolated from all structural steel and, by the use of insulating glands, from all cable sheaths. In the conductor which earths this armouring, is connected a current transformer which energises a relay controlling, by the agency of a multi-way contactor, all the circuit-breakers of the gear. To avoid accidental shutdown by accidental operation of this relay, a second relay can be installed, so that the two a.c. and the two d.c. circuits are each in series.

This system can be made safer by installing in each circuit supplying into, or supplied from, the switchgear a double-wound induction relay, the primary of which is energised by the residual current of the circuit. The secondary windings of all the relays are in series and are energised by the output current of the transformer in the earthing connection. No breaker will now be tripped unless it is carrying earth leakage current and there is a current, corresponding, which flows from the metallic armouring of the gear to earth. This method of bus-bar protection avoids accidental shut-down due to a possible rise of potential of the switchgear armouring due to causes other than insulation breakdown.

A simpler system, developed by the Metropolitan-Vickers

Electrical Co., is illustrated schematically in Fig. 146A. Here are two main relays R_1 and R_2 which respond respectively to currents in the earthing cable of the switchgear framework and in the cable earthing the neutral of the generators supplying the bus-bars. The trip circuit contacts of the relays are connected in series, and when they both operate, a multi-contact relay trips all circuit breakers of the equipment. No circuit-breaker can thus be tripped unless current appears simultaneously in the frame earth connection and in the generator neutral conductor.

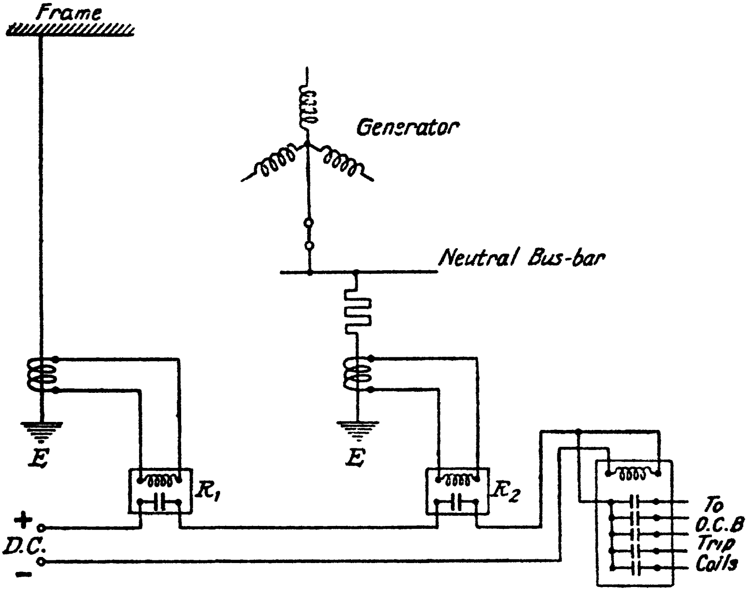


Fig 146A Bus-Bar Protection

The disadvantage of the foregoing methods of bus-bar protection lies in the necessity for the use of a multi-contact relay. In an alternative method of bus-bar protection, also due to the Metropolitan-Vickers Electrical Co., each breaker is tripped by a special associated relay on the occurrence of a bus-bar fault. These relays are of the double circuit induction type. Corresponding circuits of all the relays are connected in series to a current transformer in the conductor which earths the switchgear framework. The other circuits of the relays are each connected to an auxiliary current transformer energised by secondary residual current in the associated main circuit. The ratios of these auxiliary current transformers are so arranged that the overall ratios of the double transformations in all circuits are all equal. The secondary windings of these auxiliary current transformers, as well as being connected to the associated relays are all joined in parallel by bus wires. If the sum of the incoming residual currents is equal to the sum of those outgoing, the secondary currents of the auxiliary current transformers will circulate in the bus wires and will be diverted from the relays, which will be incompetent to operate. If, due to a bus-bar fault, the sums of the incoming and outgoing residuals are unequal, current will appear in the relay windings which, with the current in those windings supplied from the current transformer on the earth in conductor, will cause operation of the relays and tripping of the breakers. This is a very safe system, since no relay operation can occur unless, simultaneously with the appearance of current in the earthing conductor, there is an out-of-balance of the residual currents entering and leaving the bus-bars.

Notwithstanding the theoretical reliability of the methods of bus-bar protection described above, there is an influential body of engineering opinion which is opposed to the use of such schemes, on the ground that the risk of interruption of supply over large areas due to possible improper operation outweighs the advantage of protection against the remote contingency of a bus-bar fault. Engineers holding this opinion consider that the final shutting down of the supply on the occurrence of a bus-bar fault should be left to the discretion of the control engineer. An interesting suggestion has been made that bus-bar protective relay systems might be used, not actually to shut down the supply, but to give an alarm and to prepare the trip circuits of the oil circuit-breakers so that they will all be simultaneously responsive to an emergency push-button control manually actuated. An exhaustive discussion on the merits and disadvantages of bus-bar protection will be found following a paper by F. C. Winfield, entitled " Fire Precautions in Major Electrical Stations."*

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* Journal I.E.E. Vol. 81, 1937, p. 289.

Automatic Protection of Motors and Converting Plant.—The differential methods of automatic protection which have been described in application to generators and transformers are also available for such circuits as three-phase motors and converting plant when the machines are star-connected, by a comparison of the magnitudes of the corresponding currents in each line at the point of supply and at the star point. In the case of circuits which are connected to the supply system at one point only, the magnitudes and distribution of the currents in the three lines is a certain criterion of the condition of the circuit, and simpler methods of protection can be employed than in those circuits which can carry currents due to faults external to themselves.

There are four distinct conditions which give rise to abnormal currents in a circuit with one point of connection only to the supply. Two of these conditions relating to the electrical condition of the circuit, are that of a fault to earth on one line, and of a short-circuit between lines. The third condition is that of an excessive demand by the power consuming load. These three conditions may be described respectively as earth leakage, short-circuit, and overload. The fourth condition arises when one of the supply leads to the machine is accidentally opened. An induction motor will continue to run in this condition, but the current input in the other two lines will be nearly doubled. Abnormal operation of this kind is generally called single-phasing. Although this condition can be dealt with by a thermal overcurrent relay, it is generally considered to be one of urgency, calling for rapid disconnection of the machine, and protective devices for motors frequently include a device responsive to single-phasing.

The protective circuit for dealing with earth leakage faults has already been dealt with in detail. When applied to circuits of the kind under discussion, the setting of the leakage relay or trip will be as low as consistent with the necessity for stability with overload currents, and, in the case of a direct operated series trip coil, with the available output of the current transformers The volt-amperes required to operate a series trip will be considerably greater than required for a relay, and, as shown on p. 30, there will be a value of the actual secondary current setting of the trip coil which gives a minimum value of the primary current required to operate it, the volt-ampere consumption of this coil being regarded as constant.

Short-circuit currents in circuits of the kind under discussion will usually have a value many times the normal full load current of the circuit. In the case, for example, of a transformer supplying a synchronous converter or a rectifier, a short-circuit at the low voltage terminals will, for a reactance value of 15 per cent., set up a current seven times the rated full load value. Short-circuit currents will, therefore, be excessive in magnitude and protective relays to deal satisfactorily with such faults should properly have high current settings with short time-lags.

Overloads are not due to any abnormal condition of the circuit, and the excessive currents to which they give rise can safely be carried so long as no undue heating takes place in the circuit. The type of protective device inherently required for protection against overloads is one with an inverse time characteristic. When a machine is under constant skilled supervision there is much to be said for the omission from the protective scheme of any device for dealing with overloads, and for reliance on the observation of the switchman, or on the indications of a temperature alarm, so that the machine can remain in service till its overload capacity is exhausted. When a machine operates without skilled supervision, means for dealing automatically with overloads are necessary, and the best relay for this duty is the thermal type, described on p. 125. To afford adequate protection the current setting of a thermal relay should not exceed 1·1 times the current corresponding to the rated full load of the motor. In the case of induction machines, experience has shown that a thermal relay will interrupt the supply in the event of the machine stalling, before excessive heating occurs.

An even simpler method of dealing automatically with overloads is by means of a thermal tripping device incorporated in the motor itself and responsive to the temperature of the windings. With such a device, the thermal capacity of the motor is used to the utmost before the supply is disconnected. Self-contained thermal trips are however not generally deemed to be suitable for the protection of a machine against failure to start, and when there is any possibility of the supply being switched on and such a failure to be overlooked, the provision of a thermal relay in addition to a self-contained thermal tripping device is considered good practice.

The simplest device for interrupting the supply to a three-phase motor in the event of one line being opened, is a combination of three under-current relays controlling the contactor or starting switch. If the current in any line fails, the corresponding under-current relay element operates and opens the contactor or short-circuits the no-volt release of a hand-operated starter.

Short-circuit faults in a motor or its supply leads inevitably cause an unbalanced current to be drawn from the mains. A relay responsive to negative sequence currents will therefore deal with short-circuits. A negative sequence current also appears when a supply lead is opened and the machine runs single phase. Protection for both short-circuit and single-phasing conditions can therefore be obtained by a negative sequence relay, and, as such a relay is unaffected by balanced loads, its current setting may safely be made fairly sensitive and its action rapid. Negative sequence relays have already been dealt with in Chapter V, and it was there explained that a relay used in conjunction with a network connected to three current transformers in a three-phase circuit will be responsive both to negative and zero sequence currents, and will therefore, when used in a motor circuit, deal with earth leakage, short-circuit, and single-phasing conditions. A negative sequence relay energised by two line currents only will not give certain response to earth leakage currents, but as explained on p. 178 the electromagnet of such a relay can be provided with an additional winding carrying the residual current of the circuit, when it will respond to all possible abnormal conditions in a motor circuit, but that of overload. A negative sequence relay is therefore a very compact and convenient device for the protection of large motors.

An electromagnetic device, known as a stalling relay, has been developed by the Metropolitan-Vickers Electrical Co., whereby a three-phase motor is disconnected from the supply by a sustained over-current after the lapse of a definite time-lag. This relay consists of a vertical spindle Ferraris motor with the rotor normally below the position of electrical symmetry. With normal loads, the rotor stays in this position and is out of gear with the trip circuit switch. When the current reaches a stipulated value, the rotor is raised by magnetic attraction and it engages with the trip gear so that, after the lapse of a time-lag corresponding to the adjustable setting, the motor is disconnected from the supply. The rotor speed attains a limiting value for currents slightly in excess of full load, so that the actual operating time of the relay is practically independent of the magnitude of the overload. The time-lag is adjustable between 0–90 seconds. If this time-lag is set to correspond to the time during which the motor can carry the stalling current, very reliable protection will be obtained for motors which are liable to excessive overloads which may be equal to the pull-out torque of the machine.

Automatic Protection of Mercury Arc Rectifiers.—The protective arrangements for mercury arc rectifiers are generally similar to those for rotary converting plant, and include over-current and leakage protection on the supply side of the rectifier transformer. On the direct current side, a high speed reverse current-breaker is connected between the rectifier and the bus-bars. To ensure rapid disconnection of the rectifier in the abnormal condition of back-firing which, electrically, is equivalent to an internal short-circuit, the oil circuit-breaker controlling the supply to the transformer is often interlocked electrically to the reverse current-breaker on the output side, so that any feed-back from the direct current bus-bars into the rectifier completely disconnects the whole equipment. Alternatively, three instantaneous relays with a very high current setting may be used for this purpose, additional to the ordinary over-current relays.

It may be mentioned that the principle of negative sequence protection is hardly likely to find application in the control of rectifier plant due to the distorted wave form of the current input to the transformer. The efficacy of negative sequence networks is dependent upon the wave forms of the three-phase line currents being very approximately sinusoidal, since the electrical constants of these networks are suited to the fundamental frequency and would be incorrect for harmonics.

Combined Earth Leakage and Short-Circuit Protection.—We have already described on p. 59 the Z connection of the secondary windings of current transformers in a three-phase circuit, whereby protection against excessive currents in any one of the three lines can be obtained by means of two relays or trip coils. When sensitive response to earth faults is required, two over-current and one leakage relay are normally required. The simple schemes now to be described show how, by the use of time-limit fuses, complete over-current and sensitive leakage protection can be obtained with less than this normal number of relays whereby, by the use of time-limit fuses, complete protection against earth leakage or short-circuit faults can be obtained with one relay or trip coil only

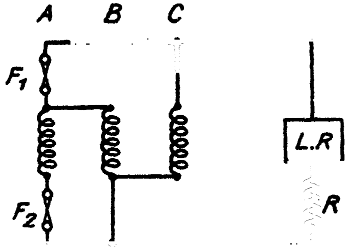


FIG. 147.—OVER-CURRENT AND LEAKAGE PROTECTION BY TIME-LIMIT FUSE AND A LEAKAGE RELAY

The first of these schemes is illustrated by the diagram of connections shown in Fig. 147. Here the secondary circuits of the three current transformers are connected in a modified star formation, and the leakage relay LR has in series with it a resistance R. In this circuit it is evident that earth leakage faults are dealt with by the leakage relay. Short-circuits between lines A and C or B and C will result in one of the fuses F_1 or F_2 being melted, so that the current from the transformer in line C passes into the leakage relay. If the short-circuit is between lines A and B the fuse F_2 will first be melted, and the current from the transformer in line B will pass through the fuse F_1 into the leakage relay. If this relay is of the instantaneous type it will at once operate, and this will be ensured by the limitation of the current by the resistance R and by the time-lag of the fuse F_1. This scheme, therefore, gives protection by means of a single relay, against both earth and short-circuit faults.

An alternative arrangement shown, in Fig. 148, is one in which complete over-current and earth leakage protection is obtained by the use of two trip coils with time-limit fuses. It is evident that leakage currents pass directly into the leakage trip. A short-circuit between lines A and B, or A and C, will melt the fuse F_1 and current from transformer A will operate the leakage trip. A short-circuit between lines B and C will melt the fuse F_2, and the current will be diverted into the over-current trip. This arrangement has the merit, as compared with that shown in Fig. 147, that in no conditions can the secondary of a current transformer become open circuited. Thus if fuse F_1 melts, due to a short-circuit between lines A and B, the secondary circuit of transformer B is closed through that of transformer C. Although this is a high impedance circuit, it will serve to prevent the inordinate pressure-rise which is liable to occur with an open circuit.

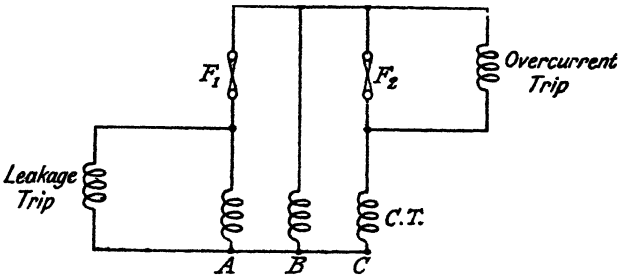


FIG. 148.—OVER-CURRENT AND LEAKAGE PROTECTION.

Another simplified short-circuit and earth-leakage protective scheme, using one relay element only is shown in Fig. 148(a). Here the two current transformers are of different ratio from the third, the two of similar ratio are cross-connected, or joined in series, and this combination is in parallel with the third having the higher ratio. The single relay element connected as for leakage protection will carry current in all conditions of loading, whether balanced, short-circuit between lines, or short-circuit to earth, although of course, the relay current per ampere of load will depend not only on its nature, but on conditions of unbalance, and on the line or lines that carry the short-circuit current. When the load supply is balanced, and the low-ratio transformers are carrying their rated full-load current,

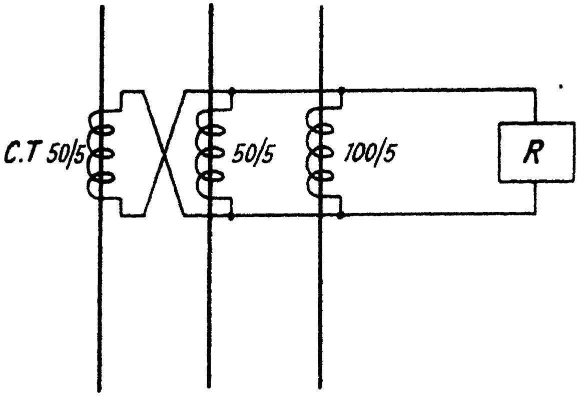


Fig. 145a

it is easy to see that the relay current is under 10 amperes, so that with a setting greater than this, the relay will respond to any kind of fault, while being unaffected by normal loading. A relay or trip-coil connected in this way may of course be shunted by a time-limit fuse.

CHAPTER VII

THE PROTECTION OF CABLES AND TRANSMISSION LINES

In modern high-pressure systems for the transmission and distribution of electric power, the object of the design of the network is to ensure that, as far as possible, each sub-station or transforming centre is supplied by at least two lines or cables, so that, in the event of a section of the network between two sub-stations becoming faulty, the supply to each of these sub-stations can be maintained. An efficient system of automatic protection must, therefore, be competent to disconnect a faulty section at each of the sub-stations at which it terminates, without the controlling breakers of any other section of the network being affected. We have already reviewed in Chapter I the evolution of protective gear which possesses this property of discriminating action, and we have seen that the various types of gear for network protection can be classified under the following four heads :

(1) Graded Time-Lag Systems.
(2) Differential Systems.
(3) Systems Employing Special Cables.
(4) Distance Systems.

In addition to these four major classes of protective gear there is a fifth class which has yet to find commercial application. This will be referred to in due course.

We now proceed to consider, in detail, these various types of network protective gear.

Graded Time-Lag Systems.—The essential characteristic of systems of this class is the use of directional relays, responsive either to excess currents or to earth leakage currents in a specified direction, having an inherent time-lag the minimum value of which is adjusted to suit the location of the relay in the network. The principle according to which the time-lags are graded will be best understood by a consideration of one or two applications of the system. The simplest example is that of a sub-station fed from a power-station by duplicate feeders, as shown in Fig. 149. The positions at which relays are installed are shown as circles, the arrow indicating the power direction to which each relay assembly is responsive, and the figure within the circle indicating the minimum time-lag of the relays. The unit in which time-lags are specified is that within which a circuit-breaker can be opened by relay operation plus a small margin for contingencies. The minimum value of this unit which can safely be adopted depends upon the type and age of the switchgear. 0·5 second is a unit time interval which would be ample for most switchgear equipments ; for modern gear, an interval of one-third second might be considered as a safe

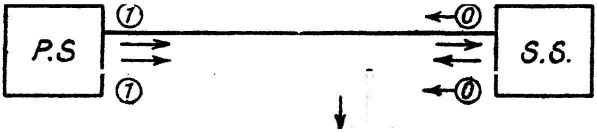


Fig. 149.—Simple Parallel Feeder Protective Circuit

minimum. In the case represented in Fig. 149, the relays at the power-station are non-directional, since the direction of power flow in these relays is invariable. This applies to the power-station relays for all graded time-lag systems. The relays at the sub-station end of the parallel feeders are directional, and respond to a power flow away from the sub-station. These relays are nominally instantaneous. A fault on either feeder will nominally result in an excess current in both of them, but as the fault current supplied by the non-faulty feeder passes to the fault in a direction contrary to that of the normal power flow, the directional relays on the faulty feeder at the sub-station end will trip the associated breaker before the completion of the time-lag of the relays of the non-faulty feeder at the power-station. The faulty feeder will be finally isolated at the power-station after the expiration of the time-lag of the relays on this feeder. If the relays are responsive to excess currents it may happen that the fault is so close to the power-station that the current fed into it by the non-faulty feeder is not sufficient to cause a net reversal of power in the faulty feeder at the sub-station end. In such a case the time-lag of the power-station relays of the non-faulty feeder will be greater than the minimum value, if these relays are of the inverse time-lag type. The faulty feeder will then be first isolated at the power-station end, when the required reversal at the sub-station end will take place and the final isolation of the feeder will immediately occur. If the relays are responsive to leakage currents, those at the power-station should be of the inverse-time pattern if the directional elements of the sub-station relays are responsive to power flow as, in this case also, failure of the power flow through the faulty feeder to reverse at the sub-station end may result

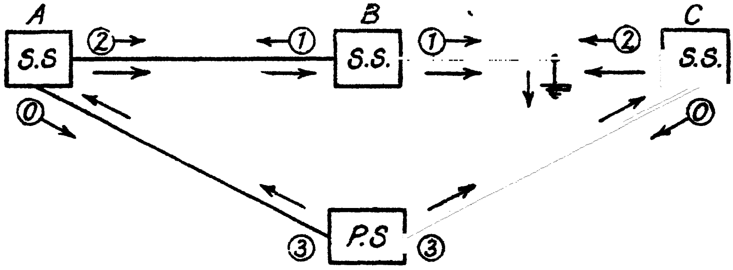


FIG. 149.—DISCRIMINATING PROTECTION BY GRADED TIME-LAG DIRECTIONAL RELAYS

in both feeders being tripped unless the operation of the non-faulty feeder relays is restrained by an increase in the time-lag. If the directional relays are energised by a residual voltage, and are responsive to a reversal of leakage current, the operating of the relays will be correct, whatever may be the position of the fault, provided the current setting of the sub-station relays is less than that of the relays at the power-station.

We shall see shortly that duplicate feeders can be protected more satisfactorily by a differential method, but we have considered the method illustrated in Fig. 149 somewhat fully as this is an elementary example of the graded time-lag system.

A more complicated example of this system is shown in Fig. 150, which shows three sub-stations fed from a power-station by a ring main. It will be seen that, proceeding round the ring in any direction, the time-lags of the relays responsive to power in this direction successively diminish, till the relay at the sub-station end of the other feed from the power-station is reached, when the time-lag becomes zero. A relay system arranged on this plan will isolate a faulty section before the expiration of the time-lags of the relays controlling the other sections. Thus, with a fault on the section BC, as shown in the diagram, power will feed into the fault from both directions. The only relays responsive to the power flow in the direction CB are that at the power-station with a minimum time-lag of three units, and that controlling the faulty section at C with a time-lag of two units. The section will thus be isolated at C before the breaker on the feeder to C is tripped at the power-station. Similarly, the relay controlling the faulty section at B will operate before any of the other relays responsive to power flow *via* A and B. As with the simpler system, shown in Fig. 149, the correct operation of the relays depends upon the magnitude of the fault current being sufficient to bring about a net reversal of power when the direction of the fault current is opposite to that of the load current. If the directional relays are of the leakage type energised by residual voltages, correct operation will be independent of the relative magnitudes of fault and load currents flowing in opposite directions.

A system in which the interconnection is a little more complex is shown in Fig. 151. Here, in addition to a ring main, we have a direct interconnector between sub-stations A and D. If a fault occur on the section CD near D, power will flow to the fault through the direct interconnector AD as well as through sub-stations B and C. The relay at A controlling the direct interconnector AD may therefore trip the associated breaker, so that this interconnector is opened at one end in addition to the faulty section. Similarly it will be found that a fault on the direct interconnector AD near D may result in the breaker controlling the section CD at C being tripped. It will be observed that continuity of supply to all sub-stations is maintained.

The graded time lag system gives reasonably satisfactory protection for small networks in which the interconnection is not very intricate. The number of stages of time-lags required depends upon the number of sections of the network. As the greatest time-lag is required in the power-station relays, faults nearest the power-station remain on the system the longest. It is this circumstance which limits the sphere of application of the graded time-lag system, as more than three stages of time-lags will retain a fault on the system for a period of time exceeding the safe limit of one second.

As was explained on page 139, the difference in the times of operation of induction relays carrying the same current depends not only on the minimum time setting, but also to some extent upon the pick-up current expressed as a percentage of the full-load current of the associated current transformer. The effective time-lag grading can therefore be improved by a careful consideration of the values of the pick-up current values, when induction relays are used for the protection of a network like that of Fig. 151. A detailed consideration of this matter in reference to a specific network is given in a paper by Gallop and Bousfield to which reference is made in the appendix to this book.

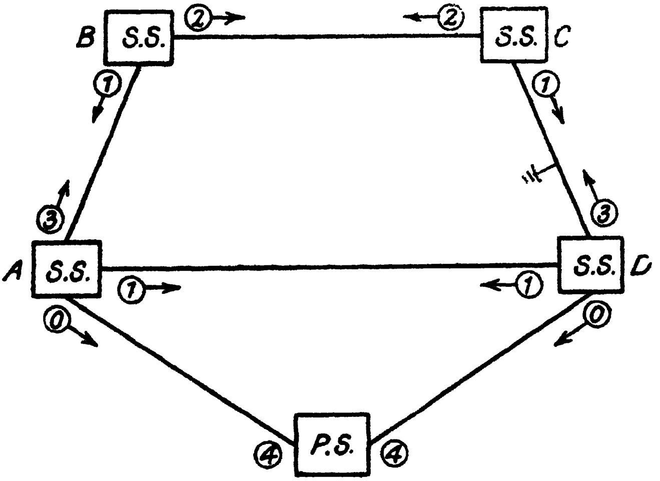


FIG. 151 —DISCRIMINATING PROTECTION BY GRADED TIME-LAG DIRECTIONAL RELAYS

When the network is formed of underground cables, the use of leakage relays with graded time-lags is justified by the fact that the majority of cable faults are due, at any rate, in their initial stages, to earth leakage. The use of directional leakage relays is generally desirable, as sensitive settings can be used, and the directional response is independent of the load currents. To guard against failure of the protective system in the event of a direct short-circuit, over-current relays should be installed in addition to the leakage relays. The settings of the stand-by over-current relays should correspond to the short-circuit currents at the points at which they are installed. It is preferable to prevent improper operation with the restricted currents due to earth leakage by adopting high current settings rather than by long time-lags.

With overhead lines the possibility of direct short-circuits is very much greater than with underground cables, as the use of over-current directional relays is almost essential.

Consideration must now be given to the matter of the correct connection of directional relays in three-phase circuits. An over-current directional relay assembly comprises three over-current elements and three wattmeter elements, and to give correct response for ordinary loading, when the voltage system is symmetrical, the voltage circuits of the directional relays would be connected in star. Provided the impedances of these three voltage circuits are identical, the potential of the star point will be graphically represented by the centroid of the triangle of the vectors of line voltages, and the current and voltage in the relays will be in phase, when the circuit power factor is unity. If a short-circuit occurs near the position where a directional relay assembly so connected is installed, the triangle of the voltage vectors will alter considerably in form due to the extinction of the voltage between the short-circuited lines. The conditions will be as shown in the vector diagram, Fig. 152, in which a short-circuit between lines B and C is indicated. The vectors of the voltages on the relays carrying the fault current are OB and OC, O being the centroid of the triangle. The fault current I lags on the line voltage BC. It is seen from the diagram that the relative directions of current and voltage in B and C phase relays are different. If the response of B phase relay is correct, that of C phase relay will be wrong. Thus the breaker controlled by the relay assembly will be tripped whatever is the direction of the flow of short-circuit power, and the discriminating feature of the protective system will be lost. The usual method of connecting the voltage circuits of directional relays is as shown in Fig. 153, in which instrument transformers are omitted. The vector diagram shows the association of currents and voltages for a symmetrical load of unity power factor. It is seen that in this condition, the currents in the relays lead the associated voltages by 30 degrees. For this reason the scheme illustrated is often known as the 30-degree connection. Referring again to Fig. 152, we see that, with the 30-degree connection, the short-circuit current in C phase relay is associated with the voltage BC and that in B phase relay with the voltage AC. The relative directions of current and voltage in the two relays is now the same, and correct directional responsive is obtained.

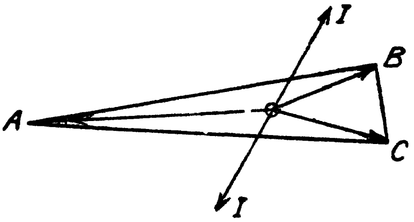


Fig. 152.—Vector Diagram of Three-phase Voltages with Single-phase Short Circuit.

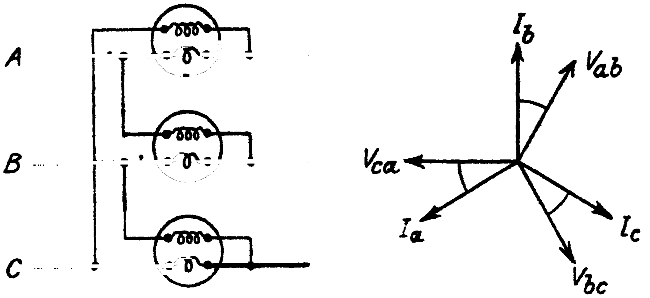


Fig. 153.—30-Degree Connection of Voltage Circuits of Directional Relays

Alternative methods of connecting the voltage circuits of directional relays have been proposed. In one of these each relay is energised by a voltage in quadrature with the current in it with unity power factor, and this phase displacement of current and voltage is corrected by internal compensation of the relay. Returning again to Fig. 153, relay B would in short-circuit conditions be energised by the voltage AC and relay C by the voltage AB As these voltages are in approximate phase quadrature with the short-circuit current the directional response will be correct.

It will be readily understood that should one of the fuses fail on the high-pressure side of a voltage transformer supplying a set of 3 directional relays, the phases of the voltages on the relays will be so modified that their action will be uncertain in short-circuit conditions If instruments are not provided whereby the secondary voltages applied to the relays can be kept under constant observation pilot lamps should be installed to enable this to be done

Differential Protective Gear for Parallel Feeders.—The protection of parallel feeders by graded time lag relays has already been dealt with and it has been pointed out that the correct operation of the relays with this system depends upon the fault currents being greater in magnitude than the load currents Differential systems of protection for parallel feeders and interconnectors depend for their correct action upon the fact that in such lines the currents always bear a constant ratio depending upon the ratio of the impedances except when one of the lines becomes faulty It is a simple matter to arrange the ratios of the protective current transformers so that, in normal conditions the secondary currents corresponding to each line are the same Fault conditions will then be indicated by an algebraic difference between the magnitudes of the secondary currents corresponding to the same phase of the parallel feeders Apart from secondary considerations arising out of departure of the ratio of the protective transformers from their nominal values load currents can be neglected in a preliminary consideration of this class of protection, and the behaviour of the relays can be studied by assuming that the only currents flowing in the protected lines are those due to faults

In Fig 154 (a) we have represented diagrammatically a pair of parallel feeders between a power station and a sub-station and on one of these feeders is a fault quite close to the power-station It is easily seen that the greater part of the fault current traverses the faulty feeder A small fraction of this fault current passes through the non-faulty feeder, through the sub-station bus bars, and back into the fault. If we assume that the currents at the sub-station end are so small as to be incompetent to operate the relays, the only effective difference in the currents in the two feeders will be at the power-station end, and this difference can be made to operate a relay which will disconnect the faulty feeder. The conditions are now as shown in Fig. 154 (b). The whole of the fault current now passes through the non-faulty feeder, through the sub-station bus bars and back to the fault. We first notice that, unless special arrangements are made to prevent it, the non-faulty feeder will tend to be tripped at the power-station end, since this feeder

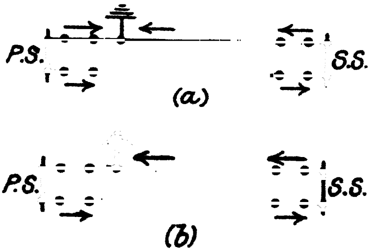


Fig. 154.—Distribution of Fault Current in Parallel Feeders with a Fault near the Sending End.

now carries the greater current. This can, however, be prevented by an auxiliary switch, actuated by each oil circuit-breaker, and so connected that when the breaker of one feeder trips, the protective relays associated with the other feeder are short-circuited. Correct discriminating action of the protective gear at the power-station end of the feeders can thus be obtained by a relay or combination of relays arranged to disconnect the feeder which carries the larger current. Considering the sub-station end of the feeders after the tripping of the power-station circuit-breaker, we see that at this end the feeders carry the same current, so that the magnitudes of the currents in the secondary windings of the protective transformers will be identical, if the ratios of these transformers are unlike. A system of relays responsive to a mere arithmetical difference in line currents will be incompetent in this situation to detect fault conditions, and the relays must, therefore, be of the directional pattern, so that the direction of the difference current circulating in the relays is compared with the invariable standard of direction given by the voltage at the sub-station. A system of relays correctly connected can be made to disconnect the faulty feeder. This feeder is then completely isolated and the load current is carried by the remaining feeder. As the differential protection at the power-station end has been short-circuited by the operation of the auxiliary switches referred to, over-current relays must be provided at the power-station end of each feeder to give stand-by protection. There will be no need for stand-by protection at the sub-station end, for the directional relays at this end will only operate with a reversal of the normal power flow when one feeder only is in service, and such a power reversal is indicative of a fault on this feeder.

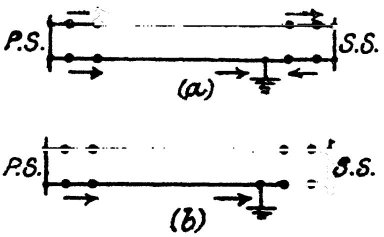


FIG. 155.—DISTRIBUTION OF FAULT CURRENT IN PARALLEL FEEDERS WITH A FAULT NEAR THE RECEIVING END.

In Fig. 155 (a) we have represented the conditions when the fault is quite close to the sub-stations. It is seen that, in these conditions, the currents in the feeders at the power-station end are approximately equal. The conditions at the sub-station end of the feeders are, however, such as to operate the protective relays. The faulty feeder will be tripped at the sub-station, and the conditions will then be as shown in Fig. 155 (b). There is now no fault current in the non-faulty feeder. The faulty feeder is, therefore, at once tripped and the second feeder carries the sub-station load.

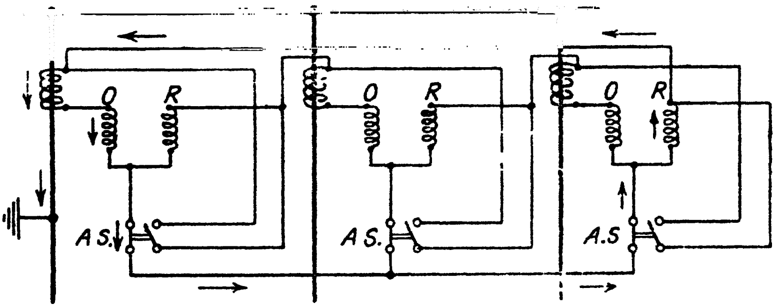
We see, therefore, that for the protection of parallel feeders, between a power-station and a sub-station, and in which the direction of power flow is invariable from the power-station, the relays for a differential method of protection need only be responsive to an arithmetical current difference at the power-station end, and that no voltage windings are called for in these relays. At the sub-station end the relays must be of the directional type.

The requirements for a set of parallel interconnectors are different from those of parallel feeders, as the normal directions of power flow is not invariable. The relays at each end must be of the directional type with voltage windings. Further, if one of a pair of parallel interconnectors is disconnected by the protective gear, the relays will, without special arrangements, be responsive to a power flow away from the sub-station in the remaining non-faulty line. The differential relays in this case, therefore, cannot, as in the case of parallel feeders, be used to give stand-by protection. These relays must be short-circuited automatically by the tripping of the breaker controlling the faulty feeder, and stand-by protection must be obtained by over-current relays with high settings.

The problem of designing an automatic protective system for three or more parallel feeders differs somewhat from that applicable to two feeders only, and discriminating protection can, in this case, be obtained at the sub-station end without the use of relays with voltage coils. A complete protective system for three or more parallel feeders should, however, be so arranged that if one of these feeders is switched out by the protective relay, the circuit is automatically adjusted to provide discriminating protection for the feeders remaining in service.

A simple type of differential relay for parallel feeder protection at the power-station consists of two over-current induction elements arranged to communicate opposing torques to a pivoted disc. Two sets of trip circuit contacts are provided, either of which can be closed by revolution of the disc from its normal position. The two over-current elements are energised by current transformers in the two feeders to be protected, and it is evident that movement of the rotor from its neutral position will only occur when the currents carried by the two feeders become unequal, due to the incidence of a fault. The direction of movement of the disc will, moreover, depend upon which feeder carries the heavier current. Such a relay can, therefore, be arranged to select the faulty one of two feeders.

The same result can be obtained by means of a single induction element with two distinct primary circuits. On one of the electro-magnets of the induction elements the two windings combine, while on the other magnet they are in opposition. A phase difference between the flux set up in the upper magnet, and that set up by a difference between the two currents in the windings on the lower magnet, is obtained in the usual way by a secondary winding, on the upper magnet, closed through a resistance. The flux in the lower magnet due to an excess current in one feeder will evidently be opposite in direction to that set up by an excess current in the other feeder. The direction of movement of the disc thus depends upon which of the two feeders carries the greater currents. The relay is thus able to select the faulty feeder. Relays constructed on the lines described are not biased, and are liable to operate with equal short-circuit currents in the two feeders due to a fault external to them if, due to imperfections of the protective current transformers, the secondary currents diverge from exact equality in these abnormal conditions.



O Operating Coil of Beam Relay
R Restraining Coil of Beam Relay
AS Auxiliary Switches, Oil Circuit Breakers Closed.

FIG 156—PROTECTION OF PARALLEL FEEDERS BY BIASED BEAM RELAYS

An application of the beam type of relay to the protection of three parallel feeders is shown in the diagram Fig. 156. Normally equal secondary currents from the protective transformers circulate in the coils of the relays, and these relays are restrained from operating even should these currents become slightly unequal when the feeders are carrying equal short-circuit currents, by the method of mechanical biasing described on p. 166. If, due to a fault on one of the feeders, this feeder carries an excess current, the corresponding excess current will pass into the cross-connections between the relay windings as shown. This excess current tends to operate the relay controlling the faulty feeder, and restrains the relays on the non-faulty feeders. The auxiliary switches shown in the diagram are operated by the main oil circuit-breakers, so that, when a feeder is tripped, discriminating protection is provided for the other feeders.

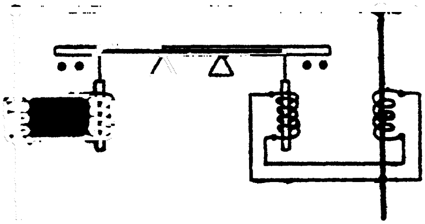
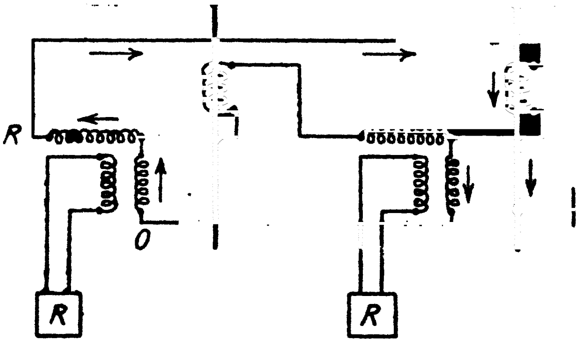


FIG. 157.—A BEAM RELAY WITH DOUBLE BIASING.



R RESTRAINING WINDING.
O OPERATING WINDING.

FIG. 158.—ELEMENTARY PROTECTIVE CIRCUIT FOR PARALLEL FEEDERS USING BIASING TRANSFORMERS.

An even simpler application of the beam type of relay is shown diagrammatically in Fig. 158. Here a single relay controls the two feeders, the direction of the deflection of the beam depending upon which feeder carries the heavier current. It will be seen that the beam rests on two pivots, and the effect of this construction is automatically to give a mechanical bias, which restrains operation of the relay to trip either feeder.

The application of the biasing transformer to parallel feeder protection is shown in the diagram Fig. 10. The restraining windings of the biasing transformers form with the secondary windings of the protective current transformers a simple circulating current system, while the operating windings of the biasing transformers are connected in series to the circulating current system in such a way that, with equal secondary currents delivered by the protective currents, no current passes into these operating windings. If one feeder, due to a fault, carries an excess current, this excess current, referred to the secondary circuit of the protective transformers. passes into the operating windings of both biasing transformer elements These biasing transformers are so designed that in order that the current delivered to the relay may reach the setting value for operation, the current in the operating winding must exceed that in the restraining winding. It will be seen from the diagram that the restraining current of the biasing transformer associated with the non-faulty feeder is never less than the operating current. The current delivered to the relay connected to this transformer is, therefore, always restrained from reaching the setting value, however great the value of the current in the operating winding may be. In the biasing transformer associated with the faulty feeder a sufficiently high value of the fault current will result in the current in the operating winding exceeding that in the restraining winding, so that the relay connected to this transformer will trip the feeder.

Figs. 159 and 160 show how the biasing transformer can be used to obtain differential earth leakage and differential short-circuit protection of a pair of parallel feeders by the use of two relays for each feeder only. Fig. 159 gives the connections for the short-circuit relays, and it will be seen that the biasing transformer differential circuit is energised from the secondary of a summation transformer connected to the secondary windings of the main protective transformers. The relays connected to the biasing transformers will, therefore, be responsive to a difference in the short-circuit currents in the two feeders between either pair of lines. Fig. 160 shows the connections for

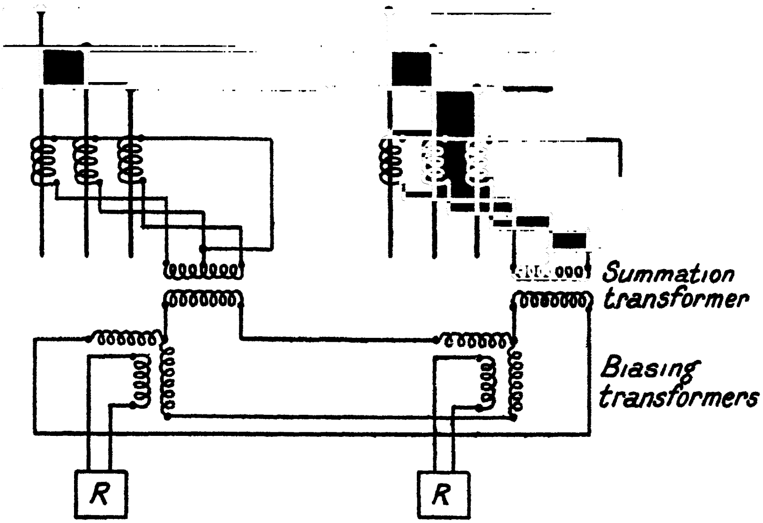


Fig. 159.—Short Circuit Protection for Parallel Feeders

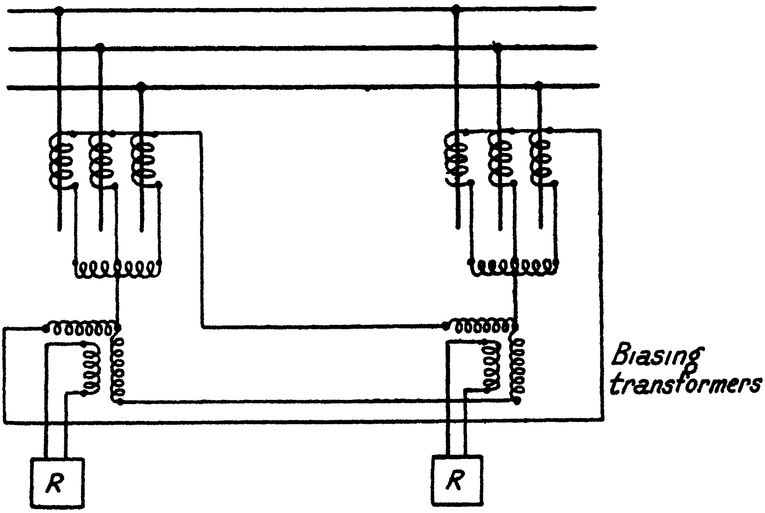


Fig. 160.—Earth Leakage Protection for Parallel Feeders

the earth leakage relays. Here the biasing transformers carry the residual currents derived from the main protective transformers, and the earth leakage relays are responsive to a difference in the earth leakage currents in the two feeders. The advantage of this system, whereby separate relays are used which respond respectively to short-circuit and earth leakage differences, is that high settings can be used with the short-circuit relays, the sensitive protection being given by the earth leakage relays. Usual values for the fault current settings with this arrangement are twice rated full load current for the short-circuit relays, and 40 per cent. of rated full load current for the earth leakage relays. Although it is usual, with this system, to provide auxiliary switches to short-circuit the relays of a feeder left on load when the other is switched out, it is evident that these switches are not so necessary as when relays responsive only to line currents are used. If, with the biasing transformer system, one feeder is switched out by relay or by hand, the load current in the remaining feeder is not likely to exceed twice the rated current of the protective transformers, so that, even were auxiliary switches not provided, there would be small risk of the second feeder being tripped by the short-circuit relay. There will evidently be no risk of an improper trip being caused by the operation of an earth leakage relay if one feeder be switched out by hand, as, in normal circumstances, there will be no residual current in the biasing transformer circuit. If, however, one feeder is switched out by relay, due to an earth fault, current into this fault will be carried by the non-faulty feeder till the protective apparatus at the sub-station operates. Auxiliary switches will be necessary, therefore, to prevent improper tripping of the non-faulty feeder due to this cause.

The rudimentary diagram of connections for the protection of parallel feeders at the sub-station end is shown in Fig. 161 for one phase only. Here the secondary windings of the protective current transformers and the current coils of the wattmeter relays are connected *in the usual way for differential protection.* The directions of the difference current in the current coils of the relays are seen to be opposed. If due to a fault on one of the feeders, this feeder carries a smaller current than does the other, the excess current from the non-fault feeder current transformer passes into the current coils of the directional relays. In one of these relays it is seen that the relative directions of current and voltage tend to operation, while in the other relay, the torque will be such as to prevent operation. The relays can, therefore, b so arranged that the feeder carrying the smaller current is tripped. It is a simple matter to provide a bias for wattmeter relays used in this way by an additional element, energised by the current in the main secondary circuit, which produces a torque of unvarying direction tending to prevent operation of the relay. The current in the wattmeter element current coil required for operation will then depend upon the magnitude of the main secondary current, and improper operation of the relays due to inaccuracies of the current transformers when carrying equal short-circuit currents will be prevented.

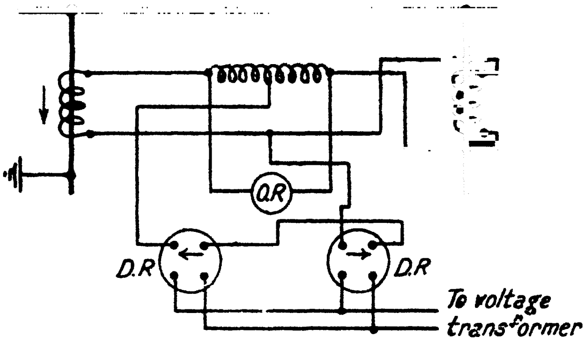


FIG. 161.—DIFFERENTIAL PROTECTION FOR THE RECEIVING END OF PARALLEL FEEDERS.

When one of the feeders is tripped by directional relay, the feeder remaining on load will evidently energise its associated relay in such a way as to prevent operation. No auxiliary switches are, therefore, required for the system shown in Fig. 161. The only condition in which the relay associated with a single feeder can operate is a reversal of the current in this feeder, and such a reversal is, of course, indicative of fault conditions.

The circuit shown in Fig. 161 is designed, not only to give discriminating protection for the two feeders, but also short-circuit protection against bus bar faults by the over-current relay

O.R. This relay, it will be seen, is connected to the whole of the winding of an auto transformer, while the connection to the differential relays is made to the mid point of this transformer. When both feeders carry equal currents the current in O.R. will be that delivered by the secondary windings of the current transformers. If one feeder only is carrying load, O.R. then carries only one-half of the secondary current. The current in O.R. thus corresponds, in all conditions, to the total current delivered by the two feeders to the sub-station.

Parallel interconnectors can normally transmit power in either direction, and in this respect they differ from feeders in which the direction of power flow is always from the power-station to the sub-station. Not only, therefore, do parallel interconnectors require differential directional relays at each end, but, if one of the interconnectors is tripped, the relays associated with the remaining interconnector may be tripped by normal load transfer. Auxiliary switches must, therefore, be provided to short-circuit the differential relays for parallel interconnectors if one of these is tripped, either automatically or by hand. A study of Fig. 161 will make it clear that, if such a protective circuit is provided for a parallel interconnector at the end which is delivering power from the sub-station bus bars, the protective relays will select and trip the interconnector which is carrying the larger current. Generally, this circuit selects for tripping, the interconnector carrying the larger current from the bus bars of the sub-station with which it is associated.

In Fig. 162 is shown a circuit for the differential protection of three parallel feeders or interconnectors. In this case it will be seen that the directional relays are energised by current only. In the case of one feeder or interconnector being tripped, the circuit would not afford differential protection for the two feeders remaining on load.

In the differential systems described above, tripping of a faulty feeder does not require that, at the sub-station end of this feeder, the direction of power flow is actually reversed, and this feature is obtained by interconnecting the secondary windings of the protective current transformers. Relays for parallel feeder protection are available which do not call for this interconnection of the current transformers. In one such type of relay, available for the protection of any number of parallel feeders, the secondary current of an induction over-current passes through two windings in opposition on the lower electromagnet, to a pair of bus wires. A directional element short-circuits one of these opposed windings when the direction of power is into the feeder. The voltages induced in all the secondary windings of the relays of a set of parallel feeders are in opposition and, with a normal distribution of the load current in the feeders no current flows from the secondary windings into the bus wires. If a fault occurs on any feeder this voltage balance is disturbed, and current flows in all the

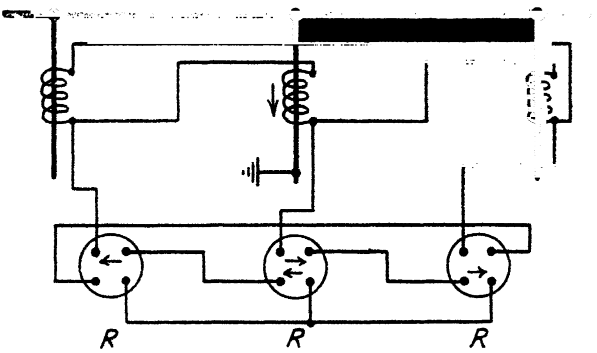


FIG. 70.—A [illegible] SCHEME FOR THREE PARALLEL FEEDERS

secondary circuits, but as the windings on the lower electromagnets are opposed, no torque will be set up, except in the relay associated with a faulty feeder in which, as has been stated above, one of the opposed windings will have been short-circuited by the directional element.

Another type of relay, designed for the protection of two parallel feeders, employs two current windings, mutually opposed, and energised respectively from the current transformers of the feeders to be protected, in both the over-current and directional elements. The direction of the movement of the disc of the directional element depends upon which feeder carries the smaller current to the bus bars. A fault in one feeder thus sets up a torque in both the over-current element and the directional element, and the trip circuit of the breaker of the faulty feeder is closed up through the trip circuit contacts of the over-current element, and those of the directional element which correspond to this feeder. Sets of three parallel feeders could be protected by relays of this type by associating one relay with each pair of feeders.

Directional leakage relays, described in Chapter V, can be used for parallel feeder protection, by arranging a differential circuit for the residual currents furnished by the current transformers of two feeders after the manner shown in Fig. 163. The voltage circuits of the directional relays are energised by the residual voltage furnished by an open delta circuit as explained on p. 60. From what has already been explained in connection with the differential circuit, it will readily be understood that the directional relays can be so connected that the one associated with the feeder carrying earth leakage current away from the sub-station bus bars tends to operate.

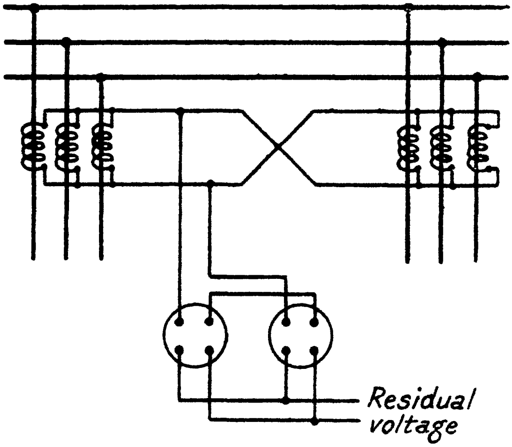


FIG 163—DIFFERENTIAL LEAKAGE PROTECTION

Reference has already been made to the necessity for auxiliary switches on the circuit-breakers at the power-station ends of parallel feeders, to make inoperative the relays of a feeder which continues to carry load after its associated feeder has been tripped. It will readily be understood that if one of a pair of parallel feeders is tripped by hand at the sub-station end, fault conditions will be simulated at the power-station end, and there will be a tendency for the other feeder of the pair to be tripped by relay. For this reason care has to be taken that when one of a pair of parallel feeders is taken off load for any purpose, the breaker at the power-station end is opened before that at the sub-station.

Switching difficulties also arise when the differential system of protection shown in Fig. 161 is used at a sub-station when it is desired to switch in a feeder that has been out of service, as the relay associated with this feeder may be in the tripping position at the instant the breaker is closed. In these circumstances the breaker will open instantly it is closed. Means must, therefore, be provided for making the relay inoperative till the feeder is made to take load by being closed up at the power-station. This can be done by connecting a spring push button switch in the voltage circuits of the directional relays. The relay associated with a feeder being placed in commission can then be made inoperative till the breaker is closed at the power-station

Merz-Price and Derived Protective Systems.--The basis of systems of this class is a comparison of the currents in each length of transmission or distribution between any two points of supply. Since the current entering such a length is identical with that leaving it in normal circumstances, any difference in the magnitudes of the currents at the two ends is a certain criterion of the existence of a fault. The problem of protecting lengths of transmission lines on this system is very similar to that of the protection of generators which has been discussed in the previous chapter. The problem is, however, rendered slightly more difficult in the case of cables and transmission lines, in that the protective current transformers are separated by considerable physical distances.

In the earliest applications of the Merz-Price principle to cable protection, the open circuit voltages of the protective transformers were opposed in a circuit such as shown. The transformers requisite for a circuit of this kind have been described on p. 45, and it is obviously essential that these transformers be so designed that the open circuit secondary voltages of two transformers so connected are equal for all values of the primary currents which may flow in the cable when carrying the short-circuit current of an adjacent section. An inequality of the primary currents will result in a resultant voltage in the circuit, and this voltage will set up a current in the relay. As the impedance of the circuit to a resultant voltage is necessarily high, the current setting of the relay will be relatively low.

Equality of the secondary voltages of the protective transformers for equal primary currents is not of itself sufficient to prevent operation of the relay if the protected cable carries the short-circuit current of an adjacent section. The voltages of the protective transformers will result in the flow of capacitance currents into the opposed voltage circuit. These currents will flow into the pilot cable from each end, and will pass through the windings of the respective relays. The magnitude of the current will be proportional to the length of the pilot cable, that is, to the length of the cable protected. The current setting of the relays must be such that these relays are inoperative with the capacitance current set up by the maximum straight-through current which can pass through the cable. The simple Merz-Price protective system by opposed voltages is thus insensitive for any but short sections of line.

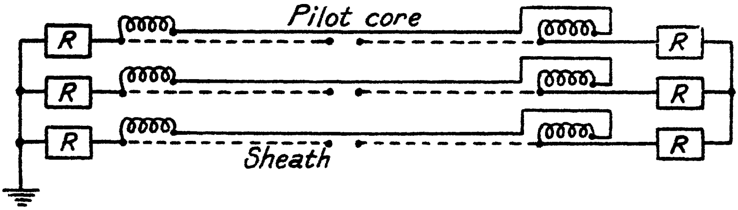


Fig. 164.—Merz-Price Protection with Sheathed Pilots

The disadvantage due to the effect of capacitance currents can be overcome by the use of a special pilot cable connected as shown in Fig 164. It will be seen that the capacitance currents due to high secondary voltages of the protective transformers flow in circuits which do not contain the relay windings, but merely comprise the transformer secondaries, the pilots, and metallic sheaths which envelop them. To prevent a circulation of current in these circuits on the occurrence of a difference in the secondary voltages of any pair of transformers, each sheath is cut at the middle point of the pilot cable. A fault on any core of the protective cable which sets up such a voltage difference will result in the circulation of a current through the relay windings, and the secondary windings of the current transformers. By the use of a screened pilot cable, very sensitive relay settings can be safely used. The cable is, however, relatively costly, although the sheathing of the pilot cores renders it possible to incorporate telephone cores and so to obtain a saving by avoiding the necessity of a separate cable for communication circuits.

Another method of overcoming the disadvantage due to capacitance currents consists in the use of a relay with two windings, the one connected directly to the current transformer, and the other to a local circuit comprising resistance and capacitance whose impedance is equal to that due to the capacitance of the pilot cable. This arrangement is shown in

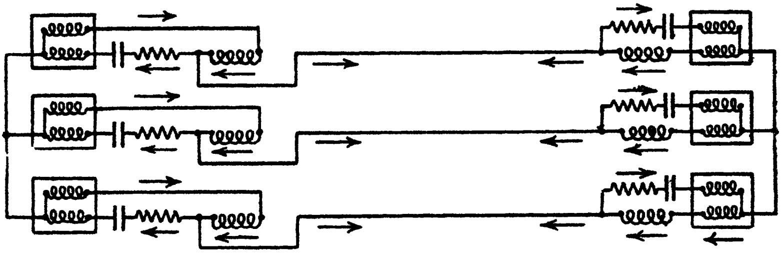


Fig. 165.—Merz Price Protection with Compensated Relays

Fig. 165, and it will be seen that on the occurrence of a high voltage in the secondary circuits of the protective transformers, currents flow in each of the windings of the relays. The circuit is so arranged that the magnetic effects of these currents are equal, so that there is practically no tendency for the relay to operate. This system is not quite so efficacious as the sheathed pilot system in eliminating the effect of capacitance currents, due to the difficulty of adjusting the impedance of the local capacitative circuit to the correct value for exact compensation.

The difficulties due to capacitance currents are largely avoided by using in the opposed voltage circuits current transformers energised by earth leakage currents as shown in the circuit illustrated in Fig. 166. When used on systems in which the neutral is earthed through a limiting resistance, the maximum value of the straight-through earth fault current which can flow in the primaries of a pair of transformers will be very restricted, and the capacitance current set up by such a current will not be such as to limit the sensitivity of the arrangement for moderate lengths of cable. With this system the relays will be responsive to earth leakage faults only, and, if a fault starts as a short-circuit, this fault will not be cleared till a breakdown of the insulation to earth takes place.

The difficulties attendant upon the use of pilot wires for the automatic protection of networks are not confined to those due to capacitance currents set up by the secondary voltages of the protective transformers. Considerable voltages may be induced in the pilot wires if single-phase earth fault current flows in a power cable adjacent. The earth fault current will return to the source of supply through cable sheaths and

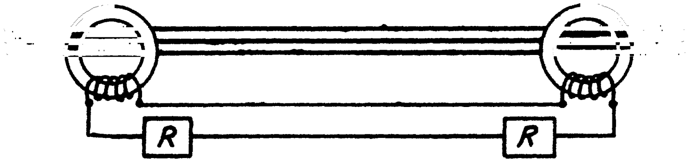


FIG 106—MERZ-PRICE SYSTEM OF PROTECTION AGAINST EARTH LEAKAGE

armourings, and if the secondary circuits of the current transformers are earthed at each end of the line, leakage currents arising from a fault on another section may find their way into the protective circuit and cause improper operation of the relays. To ensure freedom from trouble of this kind it is usual not to earth the pilot wire circuits at any point. Spark gaps can safely be provided to ensure that the pilot wire circuit does not assume a dangerous voltage, although these gaps must be set so high as not to spark over with voltages liable to be induced by fault currents.

In the transient conditions due to switching in of high voltage cables or due to the clearance of faults, sudden changes in the system voltage may give rise to capacitance currents of abnormal value. These current surges are composed of high-frequency components to which the relays will oppose an abnormal impedance. If, therefore, the relays are shunted by non-inductive resistances, these shunts will divert the high-frequency currents from the relay windings. Improper operation of protective gear by high-frequency surges of capacitance currents can also be prevented by the use of tuned relays of the type described on p. 179, as these relays will only respond to currents of the normal supply frequency

The protective circuits described above are all based on an opposed voltage principle, whereby, excepting capacitance currents, no current flows in the pilot wires except during fault conditions. We proceed to describe various systems based upon the circulating current principle which are, in effect, modifications of the circuit discussed on p. 70. Due to the high impedance of the pilot wires, the values of the terminal voltages of the protective current transformers connected for current circulation may be sufficient to set up appreciable capacitance currents, and special precautions are necessary to eliminate the effects of these capacity currents if the highest sensitivity and stability is to be obtained.

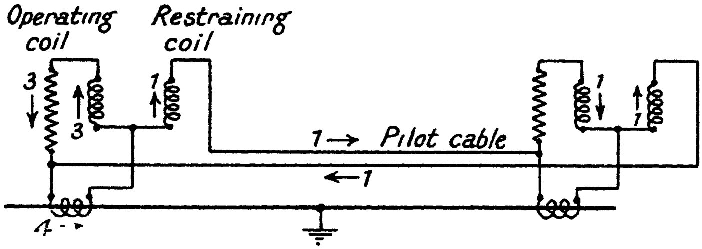


FIG. 167.—MERZ-PRICE PROTECTION USING BIASED RELAYS.

Fig. 167 gives the connections of a circulating current protective circuit in which beam type relays with mechanical bias are used. It is seen that each current transformer is connected to two circuits, the one containing the restraining coils of the relays and the pilot wires being common to the two transformers, and the second circuit, local to each transformer, containing the operating coil of the relay and an impedance of one-half the ohmic value of the pilot circuit. Normally, with equal primary currents, the secondary output of each transformer divides equally into the two circuits connected to it. The currents in the two coils of each relay are equal, and, as the pull of the restraining coil has the greater leverage, the trip circuit contacts are held open. Capacitance currents in the pilot wire flow in the restraining coils only, and increase the bias of the relay. If due to a fault, the secondary current of one transformer is greater than that of the other, three-quarters of this excess current will pass into the local circuit and the remaining one-quarter will pass through the pilot wires into the local circuit of the transformer at the other end of the line. This latter current passes through both coils of the relay at this end, and gives rise to no tendency to operation. The relay associated with the transformer carrying the heavier current has, however, three times the current in its operating coil than it has in its restraining coil. This relay will thus tend to trip its associated breaker. The current transformer at the other end of the line will then carry the excess current, and the breaker at this end will thus open immediately after the first. This system embodies the biasing principle explained fully on p. 165.

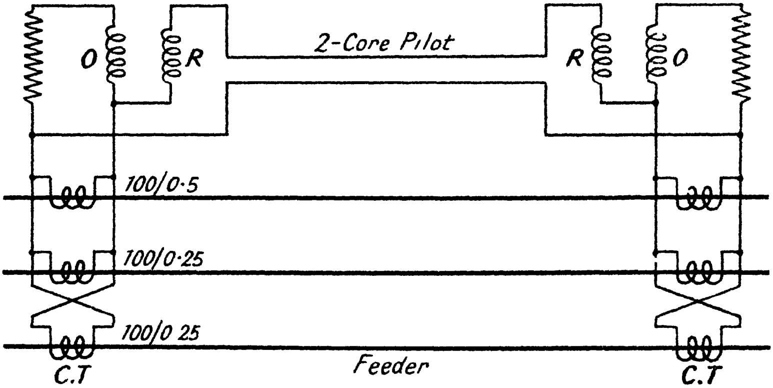


FIG 167A

The protective circuit of Fig. 167 can be used with special relays of the induction type. Each relay element has two electro-magnets, the one containing the operating winding produces a torque on a pivoted disc which tends to close the trip contacts, the other, containing the restraining winding, produces a torque tending to keep these contacts open. The impedances of the two windings are equal, but the shading rings of the electro-magnet poles are so arranged that the torque per ampere of the restraining magnet is greater than that of the restraining magnet, so that, with equal currents in the two windings, there is a net hold-off torque on the disc.

A 3-core feeder can be protected by this system in two ways. In the first, a 3-core pilot cable is used, and the three protective current transformers at each end of the line are connected in delta. An alternative method requiring only two pilot cores, is shown in Fig. 167A. Here the three current transformers of a set have different ratios, and the series-parallel connection is such that in all conditions a resultant current passes into the relay. Owing to the dissimilar ratios of the transformers the fault-current setting is different for the three phases.

The protective system whose circuit diagram is given in Fig. 168, is an interesting application of the circulating current principle in that it utilises the summation transformer described on p. 83, so that a single relay at each end of the line is responsive to both short-circuit and earth leakage faults. The secondary windings of the two summation transformers are connected in series through two wires of the pilot cables. The two relays are connected in series by the third core of the pilot cable, and joined symmetrically to the circulating current system in such a way as to equalise the burden on each summation transformer. Such a circuit would behave in the manner studied in detail on p. 74, except that capacitance currents in relay pilots, which may be set up by heavy straight-through short-circuit currents in the main circuits, would flow into the relays and tend to give rise to improper operation. The flow of the capacitance current in the relay pilot is prevented by connecting in the relay circuit the secondary windings of two small transformers, one at each end of the line, the primaries

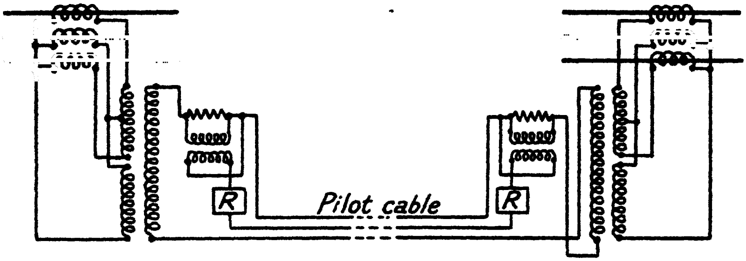


FIG 168 —MERZ-PRICE PROTECTION WITH COMPENSATING TRANSFORMERS.

of which are connected in shunt to a resistance in the circulating current system. The secondary voltage of each compensating transformer is evidently proportional to the current in the circulating current system, and, therefore, to the voltage on the pilots included in this circuit and to the capacitance current set up by this voltage. The value of the compensating voltages in the relay circuit can thus, by adjustment of the resistances shunting the compensating transformers, be made such as exactly to annul the voltages which set up the capacitance currents.

The "Solkor" protective system combines some of the features of those shown in Figs. 167(a) and 168. The main protective transformers are all of equal ratio, and, by means of a summation transformer at each end of the feeder, a voltage is obtained at each end which depends upon the feeder current: these voltages are in opposition in a circuit completed by a two-core pilot. The relays are of the rotary biased type. The operating windings being supplied from the secondaries of current transformers in the pilot circuit, and the restraining exits from auxiliary secondary windings on the summation transformers. The current transformers in the pilot-wire circuit are shunted by capacitances to prevent improper relay operation by high-frequency transients. This system was designed particularly for short feeders in high-pressure distribution networks.

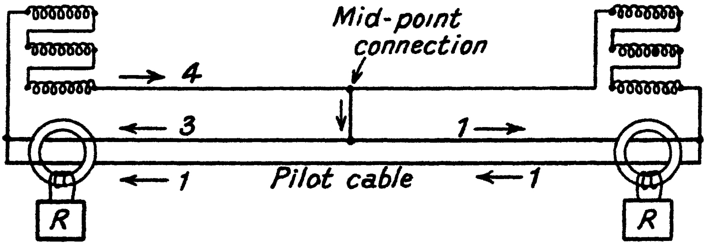


FIG 169.—SPLIT-PILOT SYSTEM OF PROTECTION.

The split pilot protective circuit, shown in Fig. 169, uses three main protective current transformers at each end of the line connected in open delta as described on p. 83. The secondary currents of the transformers flow in a circuit comprising the pilot wires. One of the pilot leads comprises two wires in parallel, so that the secondary current normally divided equally in these two wires or splits. At the middle point of the pilot cable one of these splits is connected to the other conductor of the circuit, and at each end of the circuit the two splits are connected to opposed windings of small auxiliary transformers from the secondary windings of which the relays are energised. In normal circumstances, with equal secondary outputs of the transformers at each end of the line, no current will flow in the cross-connection at the middle of the pilot, as the circuit is essentially similar to that studied on p. 63. Furthermore, capacitance currents in the pilot wires, producing equal and opposed magnetomotive forces in the auxiliary transformers, will evidently give rise to no tendency to relay operation. The behaviour of the circuit on the occurrence of a fault can best be studied by considering that one set of transformers only is delivering secondary current. This current, passing into the plain pilot wire, will divide at the cross-connection. Three-quarters will pass directly back through one split. The remaining quarter will pass along this split to the other end of the circuit and back through the second split. The relative values of these currents are shown on the diagram, and it is seen that the resultant effects of the currents in the primary windings of the auxiliary transformers are the same and are equal to that of a current equal to one-half the total secondary current passing into one primary winding. The relays at each end of the line will thus operate simultaneously. The relative values of the currents in the pilot wires have been worked out above on the assumption that the impedance of the transformer secondary windings at the end of the line not carrying fault current is considerable in relation to the pilot impedance. The effect of the impedance of these transformers in diminishing the sensitivity of a circulating current protective circuit has been fully discussed in Chapter III.

The use of Translay relays, described on p. 172, for the protection of distribution systems, illustrates a development of the Merz-Price principle in that the opposing voltages in the pilot wire circuit are derived from secondary windings on the relay elements. The principle of relays of this type has already been dealt with, and it has been explained that capacitance currents in the pilot wires produce a torque in the relay which restrains the trip circuit contacts from closing. Translay relays can be so wound that a single element at each end of the line will respond to a short-circuit fault between any pair of phases. With this method of winding a separate element is used to give sensitive protection against earth leakage faults. Fig. 170 gives the winding diagram of a Translay relay which is responsive to both earth and short-circuit faults. This winding is evidently similar to that of the summation transformer described on p. 83. The non-inductive resistance shunting the primary windings prevents operation of the relay with high-frequency transient surges in the main circuit, as with the abnormal frequencies the impedance of the relay windings will be relatively much greater than that of the shunting resistance, so that the greater part of the transient secondary current will be diverted from the relay.

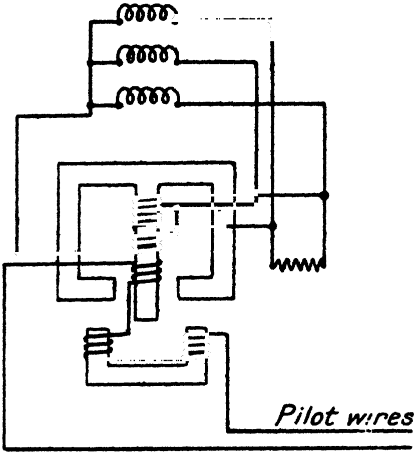


FIG. 170.—TRANSLAY RELAY RESPONSIVE TO SHORT-CIRCUIT AND EARTH FAULTS.

A method of obtaining sensitive response to earth faults and stability with straight-through short-circuit currents is illustrated by the diagram, Fig. 171. The protective transformers at each end of the line comprise two whose primary windings carry the line current, and a third, whose secondary voltage is proportional to residual earth fault current in the primary conductors. The secondary windings of the three current transformers at each end of the line are connected in series and the resultant secondary voltages are opposed in the pilot circuit. Two relays are provided at each end, the one in the pilot circuit, controlling the circuit-breaker, and the other, known as a diverter relay, in parallel with the current transformer secondaries, controlling the setting of the first relay by short-circuiting part of the resistance which shunts it. The diverter relay is not responsive to the moderate resultant voltage set up by earth fault currents and, for faults of this nature, the relays controlling the circuit-breakers have their maximum sensitivity. In short-circuit conditions the resultant voltages of the protective transformer combinations rise to a value sufficient to operate the diverter relays. This, being designed for high-speed operation short-circuits part of the shunting resistance of the main relay, which latter relay has a small time-lag provided by an inertia device as described on p. 130. The system has thus two distinct fault settings, the one sensitive, for earth faults, and the other relatively insensitive, for short-circuit faults.

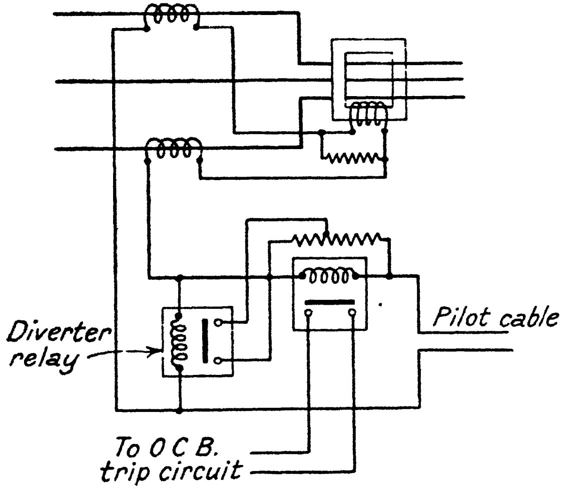


FIG. 171 —MERZ-PRICE CIRCUIT WITH DIVERTER RELAY.

Typical Fault Current Settings for Differential Protective Gear.—Differential protective gear using biased beam relays can be arranged to operate with a fault current difference equal to 10 per cent. of the balanced load current. Parallel feeder protective gear using biasing transformers will operate with a difference in the earth leakage currents equal, at no load, to 40 per cent. of the rated full load current of the circuit. Differential protection using Translay relays will operate with an earth fault current setting of about 30 per cent. Plain Merz-Price opposed voltage protection is rarely stable with straight-through short-circuit currents unless the fault current setting is over the full load current of the protective transformers.

Protective Systems Employing Special Cables.—A number of systems for the automatic protection of cable

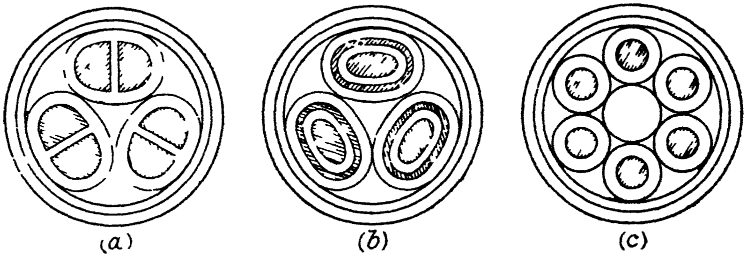


FIG. 172.—SPLIT-CONDUCTOR CABLES

systems have been devised which depend upon the use of cables of special construction. The simplest and the oldest of such systems is that using cable of what is known as the split-conductor pattern. The principle underlying this system of protection is that of providing two parallel paths within the cable of equal impedance in which the load current normally divides equally. On the occurrence of a fault in the cable, this equality of division is impaired, and a relay, responsive to the difference of the currents in the two parallel circuits or splits, trips the circuit-breaker at each end of the section.

Three patterns of split-conductor cable have been used. These, illustrated in Fig. 172, may be called respectively the segmental split, the concentric, and the six-core patterns. With cables of the first two patterns difficulties are experienced due to the fact that, notwithstanding the ohmic resistances of the two splits of any phase may be exactly equal, considerable differences may be found in the impedances. This is because the unsymmetrical arrangement of the various conductors in the cable causes a lack of balance in the inductances of the two splits constituting one phase. The concentric type of split-conductor suffers from the further disadvantage that the capacitance currents in the two splits are unequal. For these reasons it is necessary, in order to obtain an exact balance of the currents in the parallel circuits in normal conditions, to transpose the splits at such joints in the length of the section as will make each of the parallel circuits comprise the same length of conductor having a given physical position in the cable. The six-core type of cable has been found most satisfactory in practice, although, due to the high proportion of idle space within the lead sheath, it is somewhat more expensive than the segmental or the concentric types. In the six-core type, the cores situated on a diameter of the cross-section constitute the two splits of one phase. Each split is thus symmetrically situated with respect to all the others, and both the capacitances and the inductances of all the splits are exactly equal.

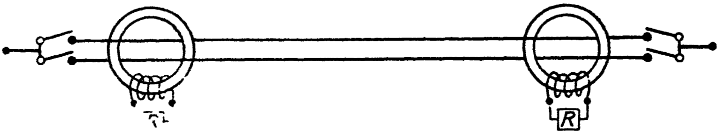


FIG. 173.—PRINCIPLE OF SPLIT CONDUCTOR PROTECTION.

The diagram, Fig. 173, shows the principle of the split-conductor system of protection. The two splits of each phase are taken in opposite directions through the core apertures of current transformers at each end of the line. It is seen from the diagram that a special pattern of oil circuit-breaker comprising two separate sets of contacts for each phase is used. The reason for this is easily explained. Consider a fault near one end of the line. This will set up a considerable inequality in the currents in the two splits at this end but the currents in the splits at the other end may be nearly equal. The difference between the currents in the two primary conductors of the protective transformer will cause the relay to operate and trip the breaker at the end adjacent to the fault. If the two splits remained connected together at this end, the currents in them at the other end would still be approximately equal, and the operation of the second relay would be uncertain. The use of a split conductor breaker ensures that the two parallel paths are separated when the breaker opens. There will now be a marked inequality in the currents entering the two splits at the end of the line remote from the fault, and the breaker at this end will be tripped by relay immediately after the first.

The use of split-conductor circuit-breakers materially increases the cost of protective gear of this class. Ordinary breakers can be used in conjunction with current transformers which have a considerable primary leakage reactance. The effect of this reactance is to limit the flow of current in the split core which is not faulty, after the breaker has opened at the end near the fault. To obtain sufficient reactance to produce the required difference in the currents in the splits in these circumstances, requires that the protective transformers have wound primaries, and the undesirable character of this requirement has led to the use of the split-conductor breaker becoming standard for protective gear of this class.

A method of using ordinary circuit-breakers and protective transformers with split conductor protection has been developed by the Metropolitan-Vickers Electrical Co. At each end of the split conductor cable, two protective transformers are used, the one a differential transformer giving a current representing the difference of the currents in the two splits, and the other a summation transformer, the secondary current of which corresponds to the total current carried by the feeder core. These two transformers supply the two circuits of a transformer type induction relay. By this method, much greater sensitivity is obtained than is possible with a single winding relay responsive to difference currents since, in fault conditions, one or other of the relay windings will carry a heavy current. When a fault occurs near the receiving end of a feeder, the primary reactance interposed in the splits by ordinary protective transformers, although small, will be sufficient to set up sufficient out-of-balance at the sending end to operate the relay with reasonable sensitivity. The current from the summation current transformer produces a small biasing hold-off torque in the relay, which prevents improper operation when the feeder is carrying straight-through fault currents.

The split-conductor type of protection responds with great sensitivity to all classes of faults but those between the splits themselves which are associated with one phase. A fault between the splits of one phase cannot be detected because there is normally no potential difference between them. The fault current settings for split-conductor gear can be of the order of 30A, provided the balance of the impedances of the parallel paths is exact.

Split-conductor protection can be made responsive to a breakdown of the insulation between splits by the modification

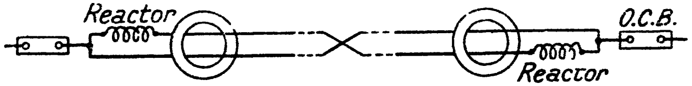


FIG. 174.—SPLIT-CONDUCTOR PROTECTION RESPONSIVE TO FAULTS BETWEEN SPLITS.

shown in Fig. 174. It will be seen that a reactor is connected in each of the parallel paths, one reactor being installed at each end of the section. The concentric type of split-conductor cable is usually employed with this scheme, the reactors being connected in the outer conductor, and the two circuits being transposed as previously explained. There is a potential difference between the two splits which is equal to the voltage drop in the reactor, and it is evident that a short-circuit between the splits will give rise to a difference in the currents they carry. This system has the disadvantages of complication of the switchgear by the use of the reactors and of increasing the regulation of the feeder, and these disadvantages more than outweigh the slight measure of additional protection obtained.

The four-conductor cable which provides a combination of both the Merz-Price and the split-conductor principles is shown in Figs. 175 and 176. One phase of a three-core cable is split into two parallel paths, and these two splits are taken at each end of the cable in opposite directions through the core aperture of a current transformer, the secondary of which is connected to the relay. The two plain cores and the two splits are also passed through the aperture of an unwound balancing core in the manner shown. Currents in the plain cores induce voltages in the closed circuit formed by the splits, which are equal and opposed, as long as the currents in each of the balancing transformers are equal. If due to a fault on either of these plain cores, the currents through the balancing transformers become unequal, the equality of the voltages in the closed circuit formed by the split core will be disturbed, a current will circulate in this circuit which will, in turn, give rise to a current in the secondary windings of the split-conductor current transformers For faults on the plain cores, therefore, the split cores are used as the pilots for a balanced voltaged Merz-Price system. A fault on either of the splits operates the protective relays according to the split-conductor principle which has been already explained. In the event of a fault at one end of the section the opening of the breaker at this end will, as shown previously, leave the fault current feeding through two parallel paths of equal resistance. The encircling of the splits by the two transformer cores is in this case relied upon to introduce sufficient reactance in the path comprising the non-faulty split, to give rise to such a difference in the two currents as will result in the operation of the relay at the end remote from the fault. Oil

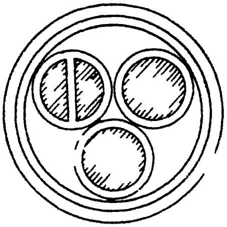


Fig 175.—Merz Hunter Four Core Cable

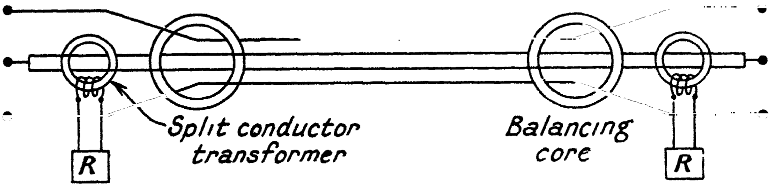


Fig 176.—Principle of Merz Hunter Four Core Cable Protection

circuit-breakers of the normal design are, therefore, used with cable of the four-conductor type.

Other cable constructions have been proposed for automatic protective purposes. Some of these are modifications of the split-conductor principle whereby the load current is carried through two parallel paths lightly insulated from each other, while others depend upon metallic sheathing of the insulated cores which, on the occurrence of a fault, becomes alive and transmits current through the primary of a protective current transformer. Cables with special internal sheaths can give an indication of an impending fault, if means are provided for keeping the insulation resistance of the sheath under continuous observation. Cables of special construction, other than those described in detail, have not, however, found any great commercial application.

Distance Protection.—We have already, in Chap. V, studied the principles and construction of relays of the distance type, and we have there seen that such relays fall into two classes, (a) those which operate with a nominally constant value of the impedance of the circuit which they control and (b) those which operate at any current of a value exceeding the setting, but with a time-lag proportional to the ratio of volts to current. Those relays in the first class are known as definite impedance relays, and those in class (b) as impedance/time or reactance/time relays accordingly as the time-lag is controlled by the total voltage, or by the component of the voltage in phase quadrature with the current.

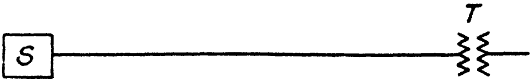


FIG 177.—ILLUSTRATING THE APPLICATION OF THE DEFINITE-IMPEDANCE RELAY

The application of the definite impedance relay will be understood by a study of the following problem. In Fig. 177 we have the single line diagram of a circuit comprising a distributing centre S, a transmission line, and a consumer's sub-station transformer which is protected locally by an inverse time over-current relay.

Suppose we require a relay at S which will disconnect the transmission line to T instantaneously on the occurrence of a short-circuit fault on this line. This requirement cannot be met by an instantaneous overcurrent relay set to operate at an estimated value of the minimum short-circuit current in the line, for this short-circuit current will vary with the amount of plant feeding into the system and with the number of sections of the network in commission. The current in the line, on the occurrence of a short-circuit fault near T, may vary within wide limits, but the ratio of the voltage at S to the current in the line will be sensibly constant and equal to the known impedance of the line. To obtain the required protection we require a relay operated by the current in the line against a restraining force which is not constant, as in an ordinary over-current relay, but which varies with the voltage at S. Such a relay is of the definite impedance class, and has been described on p. 152. If a relay of this type is adjusted to operate when the ratio of voltage to current is equal to the impedance of the protected line, corrected, of course, for the ratios of the instrument transformers, then, apart from inaccuracies of performance, the relay will operate instantaneously with a short-circuit fault at any point in the transmission line, but will be unaffected by a fault beyond the terminal point of this line.

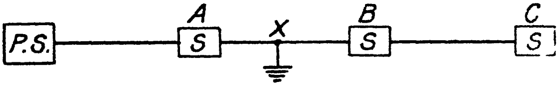


FIG. 178.—ILLUSTRATING THE APPLICATION OF THE IMPEDANCE TIME RELAY.

The application of the impedance/time relay will be understood by considering the system of sub-stations, represented in Fig. 178, as supplied by a single feed from a power-station P.S., and it is required that, on the occurrence of a short-circuit fault in the transmission lines, only the sub-stations beyond the fault shall be shut down. This result can, of course, be obtained by the use of over-current relays with graded time-lags, but this method of protection has the disadvantage that, the nearer the short-circuit to the power-station, the greater is the time which elapses before it is cleared. The required protection can be obtained by the use of an impedance/time relay, of the type described on p. 154, at the power-station end of each section of the transmission line. Let us suppose first that the line impedances between each pair of adjacent sub-stations are the same. The ratio of the voltage at any sub-station on the occurrence of a short-circuit at the far end of the section fed by it to the current in this section will thus have a constant value corresponding to the impedance of the sections. Each of the impedance relays must have its current setting adjusted so that it will operate with certainty with the minimum possible short-circuit current in the section with which it is associated, and the current in the voltage control coil must be adjusted by means of a variable series resistance so that, when the ratio of voltage to current equals the impedance of the section, corrected for transformer ratios, the time-lag has a value corresponding to the maximum time during which a fault can be retained on the system before disconnection. A usual value of the time-lag for a fault at the extreme end of a section is 0·8 seconds. With a fault adjacent to a feeding sub-station the voltage will fall nearly to zero, and the relay will operate with its maximum time-lag of about 0·2 second. The distance, time characteristics of the relays will then be as represented in Fig. 179, by the full lines. From this diagram, it will be seen that the relay at the nearest sub-station feeding a short-circuit fault will operate before that in the next sub-station towards P.S. If, for instance, a fault occurs at X, the relay at sub-station A will operate with a time-lag of 0·5 seconds. The operating time of the relay at P.S. for a fault in this position will be 1·3 seconds. There is a constant difference of 0·6 second between the operating times of relays in adjacent sub-stations.

In order that a fault may be cleared at the nearest sub-station it is essential that the breaker at this sub-station should have completed its travel before the trip circuit contacts of the relay at the next sub-station have closed. If we assume that the opening of the breaker takes place 0·3 second after the instant that the relay trip contacts close, then by drawing in Fig. 179 a series of dotted lines a distance above the full lines which correspond to 0·3 second, we have a graphical representation of the time margin between the clearing of a fault at one sub-station and the closing of the relay trip circuit contacts at the next sub-station had the fault remained on the system. We see from the diagram that this time margin has a constant value of 0·3 second.

Conceive now that the line impedances between sub-stations instead of being equal, as shown in Fig. 179, are unequal, as indicated in Fig. 180, the impedance of the section fed from the power-station being considerably greater than those beyond it. If we adjust the relay at the power-station so that a short-circuit fault at the far end of the line proceeding from it will be cleared in the standard time of 0·8 second, the distance/time characteristic will be as shown in Fig. 180. In this case we see that, on the occurrence of a fault at a position corresponding to the point X, although the relay at sub-station A will close its trip circuit contacts before that at P.S., yet the circuit-breaker at A will not have opened its contacts before the trip coil of the breaker at P.S. is energised. In this case, there will be a risk of the latter breaker operating as well as that at A and it will be necessary to increase the time-lag for the clearance of a fault at the far end of the line proceeding from P.S. to such a value that the distance/time line is always above the dotted line between A and B representing the total time between the incidence of a fault on this section and the completion of the opening of the circuit-breaker. The characteristic satisfying this condition is shown

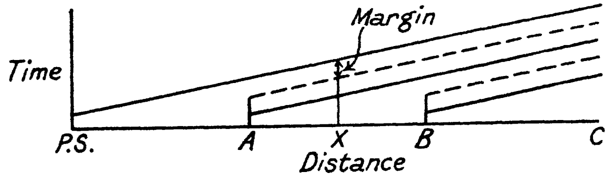


Fig. 179.—Illustrating the Application of the Impedance/Time Relay.

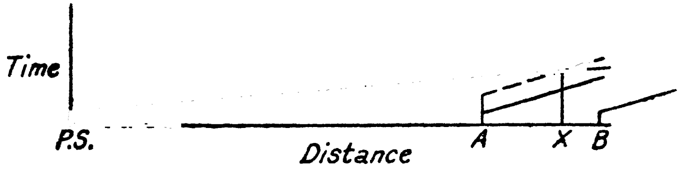


Fig. 180.—Illustrating the Application of the Impedance/Time Relay with Network Section of Unequal Impedance.

in Fig. 181, and it is seen that the maximum time during which a short-circuit fault may remain on the system has been considerably increased.

High-Speed Impedance Protection.—In order to obtain very rapid disconnection of faults near to points of supply, special high-speed distance relays have been developed,

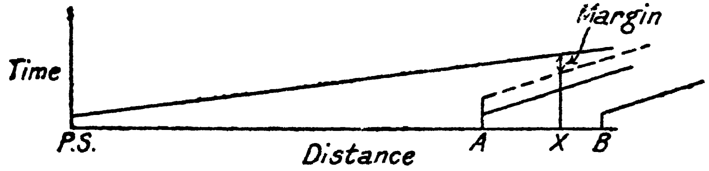


FIG. 181.—ILLUSTRATING THE APPLICATION OF THE IMPEDANCE/TIME RELAY WITH NETWORK SECTION OF UNEQUAL IMPEDANCE.

which consist of a combination comprising an instantaneous impedance component to deal with faults in the nearest 80 per cent. of the section controlled, and an impedance time component for faults in the remote 20 per cent. of the section, the latter component being set to give the standard time-

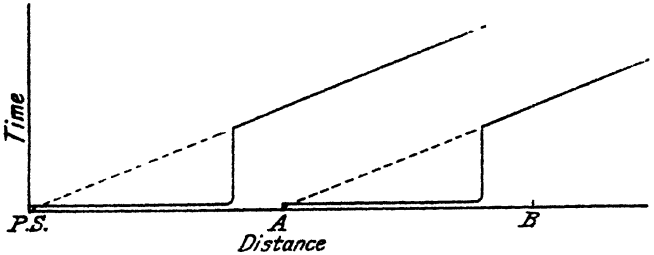


FIG. 182.—CHARACTERISTICS OF HIGH SPEED IMPEDANCE RELAY.

lag of 0·8 second for a fault at the extreme end of the section. The characteristic of such relays is as illustrated in Fig. 182. In a composite relay recently developed in America, and having this characteristic, the definite impedance component is a very light pivoted beam controlled by two voltage coils and a current coil. The fluxes set up by the two voltage coils are out of phase, so that their resultant is practically constant. When the impedance between the relay position and the fault is under the impedance setting, operation takes place within a few cycles. The impedance/time component consists of a transformer type induction element which communicates torque by a spring to a beam controlled by a voltage coil, this component being similar in principle to the relay illustrated in Fig. 103. Both of these components are subjected to the control of a directional component which consists of an inductor loop in which current is induced by a small voltage transformer and which is pivoted in the field of a current coil. This component indicates instantaneously the direction of power flow into the section by energising a small auxiliary contactor with a d.c. hold-on coil, which is short-circuited by the movement when the power flow is out of the section. A fourth component consisting of an instantaneous over-current movement operates when the secondary current reaches 8A and resets at 5A, and controls the tripping of the breaker. Thus no tripping can take place unless the secondary current exceeds 8A. When the current exceeds 8A and the direction of power flow is into the protected section, the secondary winding of the impedance/time component is closed and this component is ready to respond to fault conditions and to operate the breaker after the lapse of a time-lag corresponding to the impedance. When this impedance corresponds to fault positions in the adjacent 80 per cent. of the section, the instantaneous definite impedance component operates without time-lag and the breaker is tripped within a few cycles of the incidence of the fault.

High-speed impedance relays having characteristics similar to the foregoing have been developed by the Metropolitan-Vickers Electrical Co. The definite impedance element is set to operate for faults in the nearest 75 per cent. of the section protected. Faults beyond this point are dealt with by an impedance-time element. Constancy of the voltage flux in the instantaneous pivoted beam element is obtained by supplying the voltage coil through a rectifier. With this type of relay the time of operation of the instantaneous element is stated not to exceed four cycles with twice full-load current.

It will be understood from a consideration of Fig. 182 and of Fig. 181 that with sections of unequal impedance, there is still a risk that two breakers may open on the occurrence of a fault in the last 15 per cent. of a section. It might be thought that this possibility might be minimised by setting the definite impedance relays to operate at values of the impedance corresponding to practically the entire lengths of the respective sections. Such a procedure would be unsafe, as not only must possible inaccuracies of the relays be allowed for, but slight differences in the line impedance may arise according to the nature of the short-circuit fault. Without a margin of the order of 15 per cent. it might happen that the definite impedance relay operated with a fault just beyond the next sub-station.

Distance/time characteristics of a totally different character from those which have been considered can be obtained by the use of definite impedance relay elements with definite time-lags. Conceive that at the supply end of each section we have a relay combination made up as follows: (a) an instantaneous

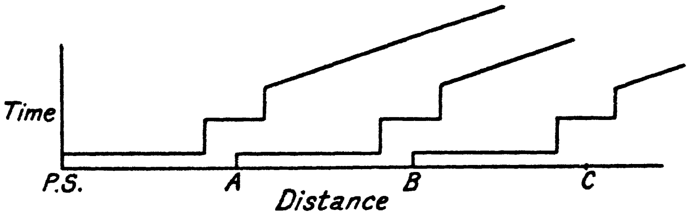


FIG. 183.—CHARACTERISTICS OF SPECIAL IMPEDANCE RELAY COMBINATIONS

definite impedance relay set to operate for an impedance equal to 85 per cent. of that of the associated section, (b) a second definite impedance relay set to operate for an impedance equal to the first section plus 15 per cent. of the second, with a constant time-lag of 0·8 second, and (c) an impedance/time relay set to operate at 1·2 seconds for a fault at the far end of the first section. The characteristic will now be as shown in Fig. 183, and it is seen that the possibility of the closing of the trip circuit contacts of a relay before the completion of the opening of the circuit-breaker controlling the faulty section is now removed. Relays with characteristics of this kind have recently been developed by the Metropolitan-Vickers Electrical Co.

If the system of distribution shown in Fig. 178 be extended so that the feed returns to the power-station, we shall have the arrangement known as a ring main. A short-circuit fault in any section can now be fed from two sub-stations. It will readily be comprehended that, by the use of directional relays controlling the over-current elements of the impedance relays in the manner explained on p. 145, or by the use of distance relays with inherent directional properties, the action of the relays responsive to the flow of fault current in both directions will be such that the relays nearest to the fault will operate with the smallest time-lag. An interesting case of a fault on a ring main occurs when the short-circuit occurs near the power-station. In such a case, the bus bar voltage at the power-station will fall to a very low value, and the voltage control of the impedance/time relays on both the faulty and the non-faulty feeders of the ring main will practically disappear. The correct discrimination in this case, whereby the faulty feeder is tripped, and the supply to the sub-stations on the ring is maintained by the alternative feed, can only be obtained by the differences of the currents in the relays on the two feeders at the power-station.

It will be clear from the foregoing discussion that the discriminating action of a protective system using impedance/time relays is obtained by virtue of the differences in the voltages applied to the coils which control the time-lags of the two adjacent relays responsive to the same direction of power flow. Experience has shown that the correct sequence of operation of a number of impedance/time relays cannot be relied upon unless, in fault conditions, the difference in the voltage applied to the control coils of consecutive relays corresponds to at least four per cent. of the normal voltage of the system. This limiting difference in the control voltages evidently is a factor which contributes to the definition of the shortest lengths of section which can be protected by relays of this type. The limiting difference defined above is equivalent to that of a minimum voltage drop of four per cent. with the minimum value of the short-circuit current. In a system in which short-circuit currents are high, a volt drop of this order may be obtained in relatively short sections, but on subsidiary medium voltage distribution systems fed by transformers of high reactance, the short-circuit currents may be not very much greater than the maximum load currents, and on such a system, the impedance/time relay would only give correct operation with sections of considerable length. Distance protection is generally used on overhead transmission and distribution systems covering wide areas, and for such duty it has been stated that the average minimum length of section which can be protected by impedance relays is about 10 miles. The distance system of protection is not suited to congested transmission systems in which a large number of sub-stations are interconnected by relatively short cable sections.

It will be advisable at this stage to discuss the limitations and sources of liability of incorrect operation of impedance relays, and on this point we summarise the conclusions of Kapp and Carrothers. The sources of error, applicable to such relays for short-circuit protection, are as follows. The question of earth fault protection by distance relays will be discussed later :—

(a) Inherent errors in the time-lag of the relay itself.
(b) Errors in the adjustment of the relay to suit the line impedance.
(c) Errors in the estimation of the magnitude of the line impedance.
(d) Errors of the current and voltage transformers energising the relay.
(e) Sluggish operation of the oil circuit-breaker.
(f) The effect of the impedance of the arc at the short-circuit.

The effect of errors in classes (b) and (c) is more serious with the definite impedance relay than with the impedance, time relay. With the former type an error in the measurement of impedance will shift the point in the section at which a short-circuit fails to operate the relay. With a relay of the impedance, time type an error of this kind will merely alter the slope of the time/distance characteristic. The effect of arc resistance on the performance of impedance relays is one on which considerable difference of opinion exists. With overhead lines, the impedance is due very largely to their reactance, while the impedance of an arc has approximately the character of a resistance. A reactance/time relay, therefore, will be unaffected in its operation by arc resistance, since, with such a relay the time is proportional to the reactance between the relay position and the fault, and this reactance is strictly proportional to the lengths of the line to the fault. It was to remove the source of error due to arc resistance that the various types of reactance relay described in Chapter V were developed. The impedance/time type of relay is, however, so much simpler than the reactance type that its use is generally preferred by distribution engineers if satisfactory performance can be obtained. It has been proposed to correct for the effect of arc resistance by reducing the voltage controlling the time-lag of the relay by an arrangement similar to that shown in Fig. 77, the correcting voltage being derived from a non-inductive resistance in the secondary circuit of the current transformer supplying the relay. This method is, however, inherently faulty, as the correcting voltage is proportional to the current, whereas the resistance of an arc is believed to fall rapidly as the current in it increases. The voltage on an arc, being in phase with the current, does not increase the magnitude of the voltage at a point remote from the fault to any appreciable degree when the impedance of the line is due almost entirely to reactance. The arc resistance will, however, tend to increase the time-lag of an impedance relay close to the fault. The trend of opinion at the present time inclines to the neglect of the effect of arc resistance in the application of impedance relays.

We now pass on to the consideration of the question of the connection and adjustment of distance relays for short-circuit protection, and in view of the fact that British and American practice favours the impedance type, we shall confine our considerations to this type.

Impedance/time relays consist *of an over-current element* and a voltage excited time controlling element. The over-current element carries a current proportional to the line current, the current transformers for a three-phase circuit being connected in star formation. The current setting is so adjusted that the minimum operating current corresponds to not more than one-half of the minimum short-circuit current referred to the secondary of the current transformers.

With definite impedance relays, however, special precautions have to be taken in the connection of the current coil for short-circuit protection due to the difference in apparent impedances of the line for symmetrical and single-phase short-circuits. If the impedance of a line between phase and neutral is Z, the current resulting from a symmetrical short-circuit with an applied line voltage V will be $\frac{V}{\sqrt{3}Z}$ in each line. With a single-phase short-circuit the current will be $\frac{V}{2Z}$. The operation of a definite impedance relay, supplied from a system of star-connected current transformers, could not differentiate between a symmetrical and a single-phase short-circuit, since this operation depends upon the ratio of line volts to line current. If, however, we connect the current transformers in delta we can obtain the required differentiation. Assuming that the short-circuit current I is equal to the full load current of the current transformers, then the current delivered to the relay with a symmetrical short-circuit will be $5\sqrt{3}$ amperes, but, as is seen from Fig. 184, the relay current with a single-phase short-circuit will be 5×2 amperes. If the line voltage is V the impedances as measured by the relay will correspond to $\frac{V}{I\sqrt{3}}$ and $\frac{V}{2I}$, and these values are in the same ratio as the actual impedances of a given length of line to symmetrical and single-phase short-circuit currents respectively.

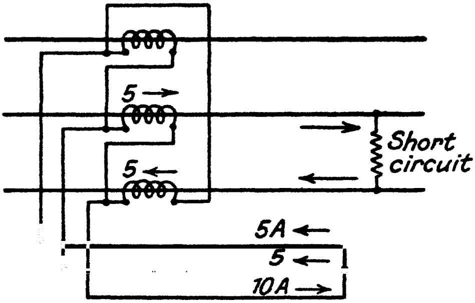


FIG. 184.—CONNECTION OF CURRENT TRANSFORMERS FOR SHORT-CIRCUIT IMPEDANCE RELAYS.

The voltage supply to impedance relays for short-circuit protection corresponds to the line voltages of the system, and these line voltages are chosen so that they lead their associated currents at unity power factor by 30 degrees. There is thus a phase difference of 60 degrees between the voltages used for the directional and the restraining circuits of a relay element. The vector diagrams for these voltages for normal conditions, and the currents and restraining voltages with a single-phase short-circuit, are shown in Fig. 185.

The current in the voltage restraint coil is so adjusted that with an applied voltage equal to that required to maintain the minimum short-circuit for a fault at the far end of the feeder, the relay will operate with the desired time-lag. This adjustment is made by a correct choice of the value of an adjustable resistance connected in series with the restraining coil, in accordance with the instructions furnished by makers of the relay. With a definite impedance relay, the normal voltage on the restraint coil is likewise adjusted to suit the desired ratio of voltage to current at which the relay should operate.

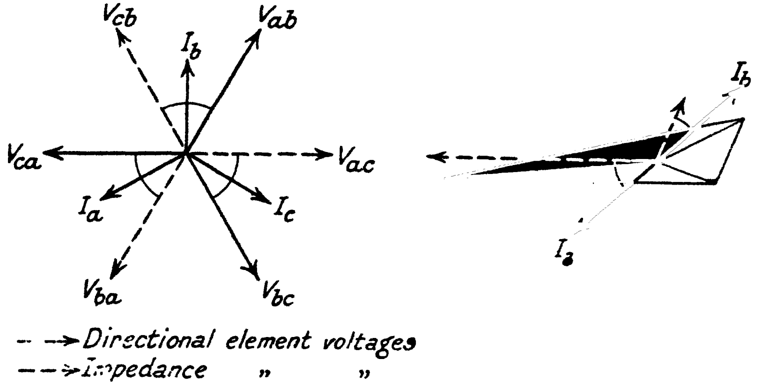


FIG. 185.—VOLTAGE CIRCUIT CONNECTIONS OF SHORT-CIRCUIT IMPEDANCE RELAYS.

Occasionally it may happen in certain extensive networks that the minimum value of the short-circuit current may be less than the peak values of the load current. In these circumstances if the current setting of the impedance relay is suited to the short-circuit current, there will be a possibility of this relay operating with load currents. To meet these conditions a special over-current relay, operative only with currents of the order of 1¼ times the maximum load current, and an under-voltage relay, operative when the voltage falls to ¾ of the normal value, are used in conjunction with an auxiliary relay, which normally short-circuits the current coil of the impedance relay. This latter relay cannot operate unless the line current rises to such a value as to operate the special over-current relay, or the voltage falls to such a value as to operate the special undervoltage relay. In either of these abnormal conditions, one of which is indicative of a short-circuit, the auxiliary relay removes the short-circuit from the current winding of the impedance relay, so that this is free to operate and clear the fault.

Distance Leakage Protection.—So far we have confined our discussion of distance protection to short-circuit faults. The application of the principles of distance protection to cover earth leakage faults is not quite so simple as in the case of short-circuit faults. In the first place we have to note that, in addition to the effect of arc resistance, that of the resistance of the earth connections has to be considered. When the connection of the neutral of a three-phase system is direct, and without unavoidable resistance, the effect of unavoidable resistance is relatively small, and is of the same character as that of arc resistance in that it slightly impairs the accuracy of relays of the definite impedance type and tends to increase the time-lag of impedance-time relays for faults near the point where the relay is installed. If, however, the resistance of the neutral earth connection is deliberately increased, with a view of limiting the earth fault currents, this limitation will reduce the potential gradient in the sections of the network due to earth faults. As the discriminating action of impedance time relays depends essentially on the voltage gradient during fault conditions, the restriction of this gradient by the use of a limiting resistance in the earthing connection precludes the use of leakage impedance relays on systems other than those in which the neutral is earthed without intentional resistance.

When there is only one earthed neutral point in a three-phase system the application of distance leakage relays is very similar to that of short-circuit relays. The leakage relays will be energised by currents proportional to the line currents, but the voltages controlling the operation of the relays must correspond to the voltages between the lines and earth. These controlling voltages are obtained from a bank of star/star connected voltage transformers arranged as shown in Fig. 186, both primary and secondary neutrals being earthed. Alternatively a star/star three-phase shell type transformer may be used. A core type transformer is useless for leakage impedance relays, as, owing to the interconnection of the magnetic circuits, the secondary phase voltages do not correspond to the primary line to earth voltages in fault conditions. The controlling voltage for a relay will be in phase with the associated current with normal conditions at unity power factor.

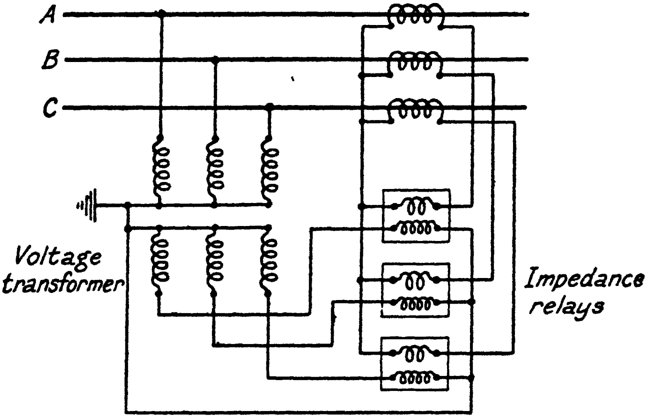


FIG. 186.—CONNECTIONS OF EARTH FAULT IMPEDANCE RELAYS.

If there is more than one neutral earthed in a three-phase system, the application of leakage impedance relays becomes much more difficult, since the impedance of a given length of line which has an earth fault depends upon the magnitude and directions of the currents in the other two lines. If reference be made to Fig. 75, showing the conditions with an earth fault on a system in which a generator and a power transformer neutral are earthed, it will be seen that, on one side of the fault, the current in the non-faulty lines is flowing away from the fault and back to the generator, while on the other side of the fault the line currents are equal and in the same direction. The impedance per unit length of the line carrying fault current in the former condition is less than that in the latter, so that the ratio of line to earth voltage to line current at any point is not a measure of the distance of the fault from that point. According to Kapp and Carrothers the impedance of a given length of line, as measured by this ratio, varies with the ratio of residual current to current in the faulty line, according to the graph shown in Fig. 187. The value 3 for this ratio is applicable to the conditions between the fault and the power transformer in Fig. 75. A value of 1 would correspond to conditions in which the transformer is switched out, so that the only line current is that feeding into the fault. A zero value of the ratio corresponds to the conditions in Fig. 74 between an earth fault and a delta-connected generator. It is seen that the apparent impedance of a length of line varies so greatly with

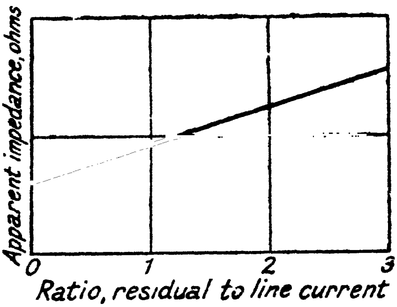


FIG. 187.—VARIATION OF APPARENT IMPEDANCE TO EARTH FAULT CURRENTS.

the distribution and magnitudes of the currents in the three lines, when an earth fault occurs on a system with multiple earthing, that the performance of impedance relays energised by line currents and line to earth voltages would be hopelessly inaccurate.

The graph in Fig. 187 shows that the greater the residual current in relation to the current in the faulty line, the greater the impedance as measured by the ratio of line-to-earth voltage to line current. In order that the apparent impedance measured by the relay may always be equal to the standard impedance value for no residual current, the current in its current coil must be increased by an amount proportional to the actual residual current. This increase of the relay current will cause it to operate in accordance with a lower impedance value, and by a suitable choice of the fraction of the residual current superimposed upon the secondary line current in the relay current coil, the value of the apparent impedance as given by the ratio of relay voltage to resultant relay current can, for a given length of line, be made nearly independent of the distribution and directions of the line currents on the occurrence of an earth fault. According to Kapp and Carrothers, the fraction of the secondary residual current to be compounded with the secondary line current is very nearly one-half. The manner in which the two currents are compounded is shown, for one phase only, in Fig. 188. It will be understood that the superimposition of the residual current on the line current in the relay increases the relay current corresponding to the faulty line, but decreases the relay current corresponding to the other lines. The time-lag of the relay operation, therefore, is determined by the element corresponding to the faulty line.

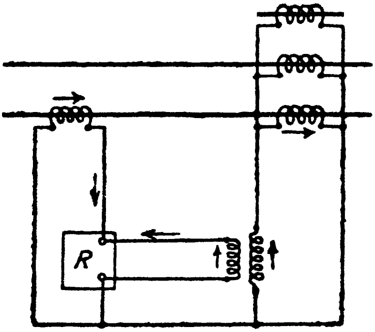


FIG 188 —COMPENSATED EARTH FAULT IMPEDANCE RELAY.

Fig. 189 shows the connections of a combined earth fault and short-circuit impedance relay. There are two elements, a definite impedance element connected for earth fault protection, and a directional impedance time element connected for short-circuit protection. On the incidence of a short-circuit fault, the impedance time element operates in the usual way. The incidence of an earth fault operates the definite impedance element if the fault lies within the range of this relay, and its operation short-circuits the voltage restraint of the impedance/time element so that it operates with the minimum time-lag. If the fault lies without the range of the definite impedance element, an auxiliary residual current or leakage relay short-circuits part of the series resistance of the voltage restraint circuit and connects this circuit between the faulty phase and the voltage transformer neutral. The impedance/time element then operates as a distance earth leakage relay.

Negative Phase Sequence Protection.—All methods of automatic protection depending on time-lags graded either

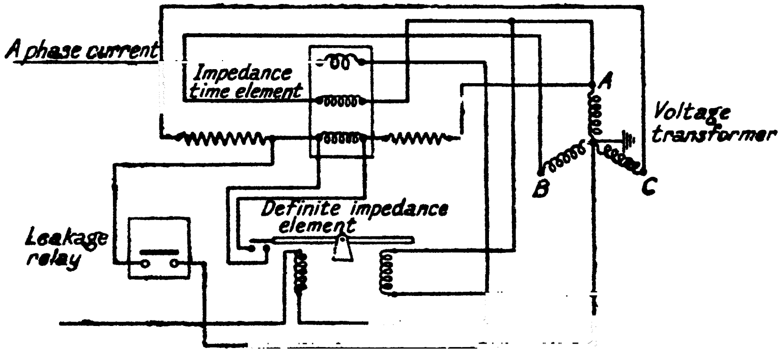


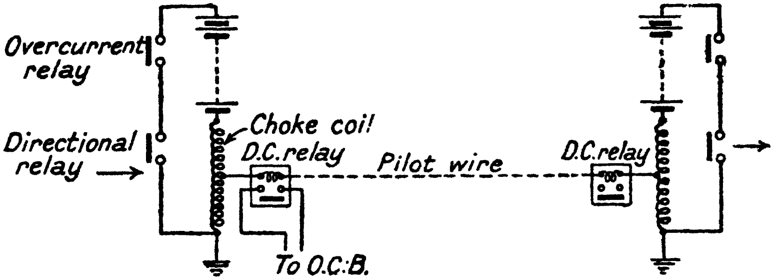
FIG. 189.—COMBINED SHORT-CIRCUIT AND EARTH FAULT IMPEDANCE RELAY.

automatically, by impedance control, or by hand adjustment can theoretically be used with relays energised by negative sequence currents and voltages, giving unique response to short-circuit and earth faults. Although, for moderate voltages, negative sequence directional relay equipment is more complicated than directional leakage relays, this is not so for very high voltages. A directional leakage relay requires a special type of voltage transformer with an earthed star point to obtain the residual voltage. A negative sequence voltage can be obtained from a three-phase voltage transformer of an ordinary pattern or from a V-connected bank of single-phase transformers. Since an earth fault residual current and the consequent residual voltage each contains a negative sequence component, a negative sequence directional relay will respond correctly to earth fault as well as short-circuit faults. Relays of this type are now used to some extent for directional leakage protection instead of those energised by residual currents and voltages.

Another condition in which negative sequence relays are used is that in which the short-circuit current in a line is comparable with the rated full load current. Such a condition is found when a distribution transformer is directly connected to a transmission line without an intervening automatic circuit-breaker. A short-circuit fault on the low pressure side of the transformer will give rise to a current in the line, the magnitude of which is limited by the transformer reactance and which may be relatively small. A fault of this kind can hardly be dealt with by any relay depending upon mere current magnitude but is controlled with certainty by relays at the terminal points of the transmission line which are responsive to negative sequence currents.

D.C. Pilot Wire Systems of Protection.—A number of systems for the protection of cable networks have recently been developed which make use of pilot wires connecting the D.C. tripping circuits of the circuit-breakers controlling the two ends of the protected section. These systems have not, at the time of writing, been tested in practical application to any extent, but they appear to give promise of excellent results. The possibilities of D.C. pilot protection are manifold, and admit of many developments. So far, the systems proposed depend upon two principles which will be briefly explained.

It will be understood that one of the criteria of the existence of a fault on a length of cable or transmission line between two points of supply is the simultaneous feeding of power into both ends of the length. Some twenty-five years ago it was suggested by Dr. Garrard that this principle might be utilised for the protection of networks by interconnecting the trip circuit contacts of directional relays at each end of a section in such a manner that the tripping of both breakers occurred simultaneously when both relays had closed their trip contacts. Fig. 190 shows the connections of a D.C. protective circuit in which operation of the circuit-breakers depends upon simultaneous feeding of power into both ends of the section. At each end of the section is a circuit comprising a battery and choke coil, and in this circuit are connected the trip circuit contacts of a directional and an over-current relay. Corresponding taps on the choke coils at the two ends are joined by a pilot wire, and connected in the pilot circuit are two D.C. relays, one at each end of the line. It will be seen that the trip circuit contacts of the directional relays are so arranged that power flow into the feeder at one end closes the relay contacts, while power flow into the other end keeps open the contacts of the relay at this end. Short-circuit current flowing through the section will, therefore, close the local circuits at each end, and as the battery voltages are equal, the potentials of each end of the pilot wire will be equal and no current will flow in the pilot wire circuit. If power flows into each end of the section, only one local circuit will be closed. Current will now flow in the pilot wire, energising the D.C. relays which, in turn, close up the trip circuits of the breakers and isolate the section. The choke coils are used to prevent the ingress of alternating current into the protective circuit during fault conditions when considerable differences of potential may exist between the two earth connections. This current would not, of course, operate the D.C. relays, but might be of sufficient magnitude to overheat their operating coils. Due to minor drawbacks this simple scheme has not been commercially developed, but it is described here in order to illustrate the fundamental idea underlying the D.C. pilot system of protection.



Directional Relay Contacts close when Power Flow is as shown

Fig 190.—D.C. Pilot Wire Protection.

A special design of directional relay is required in connection with the D.C. pilot wire system of protection. The apparently obvious method of closing the local D.C. circuit by using three single-phase directional relays with their D.C. switches connected in parallel is not admissible, since the directions of power flow in the three lines may be different with a fault external to the protected section. A false indication would then be given by fault current feeding into one line of the section while load current fed into the section by another line. A single three-element directional relay is, therefore, used in which two elements are connected to respond to the power flow into the line considered as a three-wire circuit. The third element is connected as a directional leakage relay, and is made relatively more sensitive than the other two elements.

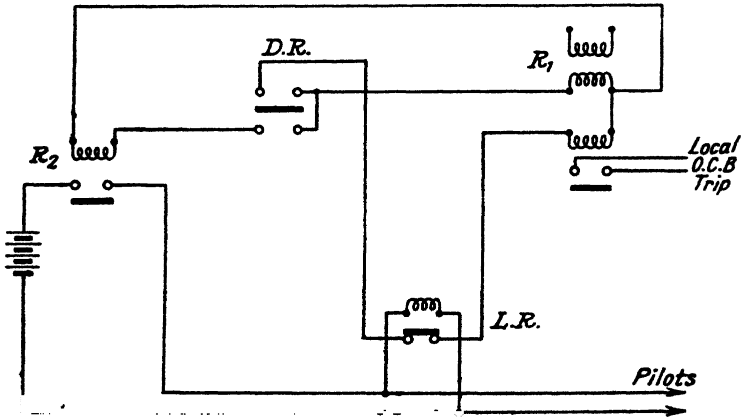


FIG. 191.—LONGFIELD LOCK-IN SYSTEM OF D.C. PILOT PROTECTION

In a more modern type of directional relay there are four wattmeter elements which communicate torque to two discs on the moving element. Three of these elements are responsive to line currents and line voltages, with the 30-degree connection described in Chapter V. The fourth and most sensitive element is energised by residual current and voltage and is a directional leakage element.

Fig. 191 is a schematic diagram of connections of the Longfield lock-in system of D.C. pilot protection which has been commercially developed by the Metropolitan-Vickers Electrical Co. The underlying idea of this system is that when power is flowing out of a feeder at one sub-station, the controlling relays in the sub-station at the other end of the feeder are made inoperative. The feeder is, therefore, tripped automatically when, and only when, power is flowing into it at both ends. D.R. is the double-throw switch of a four-element directional relay. R_1 is one of a set of three over-current relays, one for each phase, the operation of which can only take place when power flow is into the feeder. This relay is of the induction pattern and operates with a small time-lag. The operation of R_1 is also controlled by a locking relay L.R., the operating coil of which is connected to the pilot cable. If these pilots are energised from the far end, the auxiliary contacts of L.R. will open and R_1 will be unable to operate. Energised from a secondary winding on the over-current relay R_1 is a second over-current relay R_2, instantaneous in action. This relay can only operate when the direction of power flow is out of the feeder, so that the second pair of contacts in D.R. is closed. The effect of the operation of R_2 is to connect a battery to the pilot wires.

To study the action of this protective system, suppose first that there is a fault in the line which it controls. Power flows into the line at each end, and after the lapse of the small time-lag, the relays R_1 at each end operate and trip the associated breakers. The pilot wires are not energised. Suppose now that the line carries a straight-through fault current. The power direction as indicated by D.R. is, say, out of the feeder. R_2 operates instantaneously and energises the pilot. At the other end of the line, the power flow direction is inwards, but before the trip circuit contacts of R_1 can close, the locking relay L.R., energised by the pilots, will open the secondary circuit of R_1 and render it inoperative. The line will therefore remain connected to the system.

The preceding description of typical D.C. pilot wire systems of protection will suffice to demonstrate the possibilities of this method of using pilots, and considerable development of these systems may be expected in the near future. The advantages of using D.C. pilot wires are manifest. The need for balancing protective transformers at the two ends of the section is eliminated, and the voltages imposed on the pilot are restricted, so that pairs in standard telephone cables can be used for the protective circuit.

The directional relays used for D.C. pilot wire protection have been described above as being of the three-phase power and leakage type. A possible development of this system consists in the use of directional relays responsive to negative sequence power and zero sequence, or leakage power. We have seen above that the presence of negative sequence power is a certain criterion of the incidence of a short-circuit fault on a transmission system, and, since an indication of the direction of power of this phase sequence can be obtained by a single directional element, relays responsive to negative and zero sequence power will be simpler, and can be made more sensitive than those depending on excess values of the line current for operation.

CHAPTER VIII

THE TESTING AND MAINTENANCE OF PROTECTIVE GEAR

THE general subject of the testing of protective gear comprehends not only that of the instrument transformers and relays which are the component parts of the gear, but also the checking of the correctness of the assembly of these components and their connections to form a protective circuit The testing of current transformers to determine their suitability for use in a protective circuit has been sufficiently dealt with in Chapter II. The conditions under which voltage transformers operate in protective circuits give rise to no appreciable errors, having regard to the wide limits of error allowed in the performance of protective apparatus, and the testing of voltage transformers, therefore, calls for no comment. All that remains to be dealt with under the heading of testing is that of the protective relays and their assembly into a protective circuit.

The testing of relays covers the experimental determination of the relation between the currents and voltages in the relay circuits and the time-lag in operation. Two questions arise in this connection which lie without the scope of ordinary electrical measurements; the supply of the testing current, and the measurement of the time-lag.

Source of Testing Current.—Tests on relays with currents considerably higher than the nominal setting call for some care in the arrangement of the test circuit, as the time-lag of induction over-current relays operating under considerable overloads is affected to a marked degree by the wave form of the test current. Economy and convenience of regulation is often sought in the arranging of relay test circuits by connecting the relay directly to the low voltage terminals of a transformer energised by the supply mains. Due to magnetic saturation, an induction relay so connected will tend to produce a distorted wave of secondary current, and tests have shown that with a test current of the order of ten times the nominal setting the time-lag may vary by as much as 20 per cent., using test circuits which would generally escape criticism.

Distorted waves of current are produced in circuits fed by a sinusoidal voltage source in which the impedance is not constant. Magnetic saturation leads to an impedance which diminishes as the current increases, the wave form of the current in this case being peaky.

The circuit which gives rise to the greatest wave distortion is that shown in Fig. 192 (a). Here coarse regulation is obtained by a multi-tap auto transformer, and fine regulation with a resistor in the primary circuit. If the primary series resistance is all cut out, the wave form of the relay current will be determined almost entirely by the variations of the relay impedance, and a very distorted wave form will result for high values of the relay current. Small amounts of resistance in the primary circuit will tend to reduce the variation in the impedance of this circuit, but the wave form will always be poor.

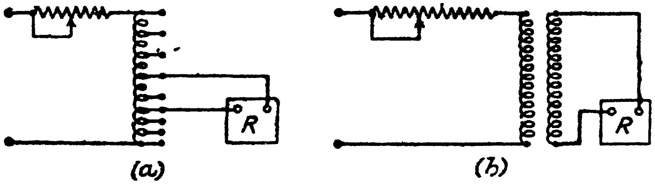


FIG. 192.—UNDESIRABLE TEST CIRCUITS, LIABLE TO GIVE DISTORTED WAVE SHAPES OF TEST CURRENT.

An alternative arrangement is shown in Fig. 192 (b) in which the relay is supplied from the secondary of a constant ratio double wound transformer, regulation being effected by means of a variable resistor in the primary circuit. The wave form of the relay current will now depend upon the rating of the test transformer and upon the amount of resistance in the primary circuit. If the primary voltage of the transformer is but a small fraction of the supply voltage, the primary current will be very nearly sinusoidal, and the secondary current wave form will differ very little from that of the primary. If the primary voltage of the transformer differs but little from the supply voltage, the variable secondary impedance will largely determine the wave forms of both primary and secondary currents.

The best circuit for testing relays is that shown in Fig. 193, in which the relay is supplied direct from a constant voltage source in series with a variable resistance. With heavy overload currents there is a possibility of slight distortion of the current wave, but this possibility can be avoided by connecting

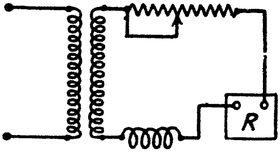


Fig. 193.—Test Circuits in which Wave Distortion is Avoided.

an air cored inductance in the circuit as shown. An inductance of about $1\frac{1}{2}$ ohms is sufficient to maintain a sinusoidal wave of test current up to the highest values required.

A suitable variable voltage test circuit, which avoids the necessity of drawing heavy currents from the supply mains is shown in Fig. 194. Here a multi-tap auto-transformer supplies the relay with an air cored inductance of approximately 1·5

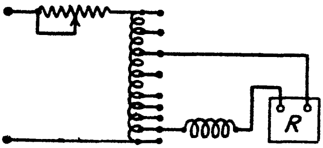


Fig 194.—Test Circuits in which Wave Distortion is Avoided.

ohms in series. Fine regulation of the test current is obtained by means of a variable resistor in the primary circuit.

The general principle to be borne in mind in setting up relay test circuits is that of the necessity of the preservation of a sensibly constant impedance of the circuit. Air cored inductance coils are more efficacious than resistors in preserving this constancy of the circuit impedance, since the reactance of the inductor tends to restrict the high-frequency harmonics in the current wave which produce distortion.

An important point arises in connection with the testing of sensitive relays, of the nominally instantaneous class, having very low current settings. For such tests, lamp resistances are very convenient, and the fact that metal filament lamps of low rating are easily obtainable suggests the use of lamps of this type for obtaining small testing currents. The shape of the volt-ampere characteristic of a metal filament is, however, such that large errors are likely to occur in the experimental determination of instantaneous relay settings if the current in the circuit is limited by these lamps. The resistance of a metal filament lamp, when cold, is considerably greater than when it is carrying its normal current, and the initial rush of current which takes place in the filament of such a lamp when it is switched on to the supply is shown in Fig. 195. An instantaneous relay with a light movement will be so far affected by this current rush that it may trip with a current whose steady value is only about three-quarters of the true setting obtained by the use of a test circuit of constant resistance. The use of metal filament lamps should therefore be avoided in relay testing. The resistance of a carbon filament lamp is greater cold than when it is carrying its normal current. The use of lamps of this type for testing instantaneous relays will, therefore, lead to no error in the determination of the minimum operating current, but the time-lag in the establishment of the steady value of the current may introduce a slight but appreciable time-lag in the operation of the relay with currents in the neighbourhood of the setting value. Both classes of

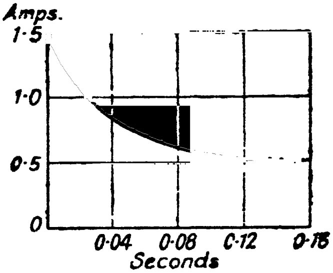


FIG. 195.—CURRENT TIME CHARACTERISTIC OF METAL FILAMENT LAMPS.

error can be completely avoided by the use of wire resistances for testing sensitive instantaneous relays.

The Measurement of Time-Lag.—Measurements of the time-lag in the operation of protective relays are almost invariably made by means of a time interval meter The internal

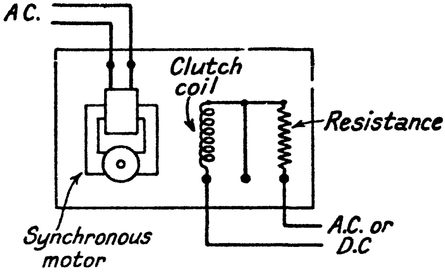


Fig. 196.—Time Interval Meter.

connections of this instrument are shown diagrammatically in Fig. 196. The rotor of a synchronous motor drives the principal spindle through appropriate gearing at a nominal speed of one revolution per second. The rotation of this spindle is communicated to a pointer which revolves over a dial graduated in 1/100ths of a second by means of an electrically operated clutch, the coil of which is connected in series with a resistance. The clutch coil circuit can be operated from either a D.C. or an A.C. source, and the clutch coil can be deenergised, either by disconnecting the source of supply, or by short-circuiting the coil, when the full voltage of the clutch

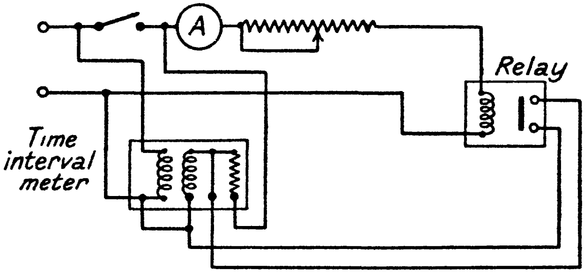


Fig. 197—Test Circuit for Relay with Circuit Closing Contacts.

supply is taken by the series resistance. A subsidiary dial, with a pointer geared to the main spindle, gives indications up to 10 seconds.

The inherent time-lag of a relay can be conveniently tested by arranging that the supply to the clutch coil circuit is established simultaneously with the switching on of the test current. The trip circuit contacts of the relay are so connected as to short-circuit the clutch coil when the travel of the relay is completed. The diagram of connections for a test on these lines is shown in Fig. 197. If the relay switch is of the circuit opening type, the connections are arranged as shown in Fig. 198. Here the completion of the travel of the relay opens the clutch coil circuit of the time interval meter.

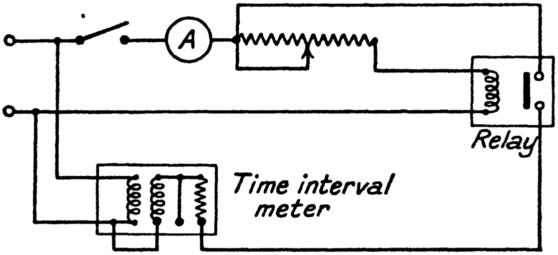


FIG 198.—TEST CIRCUIT FOR RELAY WITH CIRCUIT OPENING CONTACTS

An interesting home-made timing device has been described by R. B. Rowson, in a paper mentioned in the Appendix. This instrument is a modified low-current A.C. supply meter. The current coil is energised by a secondary winding on the voltage magnet. A neon lamp is fixed in the case of the meter so that, by stroboscopic examination of the divided disc, the speed can be set on site to a standard value by adjustment of the brake magnet position, an external knob, being provided for this purpose. An auxiliary circuit is provided for inching the disc to give zero reading. The instrument is started by the switching on of test current and is stopped by the action of the relay. As, apart from friction, the control is by the brake magnet, the starting error is cancelled by the stopping error so that the travel of the disc is a measure of the time of operation of the relay tested. The actual error, as measured by a standard time interval meter is said normally to be under 1/20 second, and not to exceed 1/10 second. A device of this kind is a useful alternative or auxiliary spare to the more expensive kind of instruments.

Relay Testing.—In the discussion of the principles and construction of protective relays in Chapter V, we opened with a consideration of the characteristics of the time limit fuse, and it was there shown that, if a number of corresponding values of fusing current and time were experimentally determined the characteristic could be obtained in a linear form, so that the maximum current the fuse would carry indefinitely could be obtained by the intercept of the characteristic on the vertical axis of co-ordinates. Fig. 199 gives the connections of a circuit for obtaining experimentally a number of points on the characteristic curve of a time limit fuse. In this circuit R_1 is a resistance having an ohmic value equal to that of the fuse and the resistance connected directly to it. The use of this resistance R_1 enables the value of the test current to be adjusted to the required value without this current passing through the fuse. When the double throw switch is put into the position for passing the test current through the fuse, the clutch coil circuit of the time interval meter is energised and this meter commences to register. When the fuse melts the voltage on the clutch coil disappears, and the meter ceases to register. The reading of the time interval meter, therefore, gives the period during which the fuse was carrying the test current. As the range of standard time interval meters is 0-11 seconds, care must be exercised, when using currents little in excess of the limiting value, that a complete revolution of the auxiliary dial of the meter is not missed.

In the testing of thermal over-current relays a circuit similar to that shown in Fig. 199 can be used, but the long time-lags given by these relays are not very conveniently measured by an ordinary time interval meter. A more convenient timing device is an ordinary self-starting synchronous motor clock, connected to the supply voltage in series with a lamp, the trip circuit switch of the relay being so connected that it short-circuits the clock when the relay operation is complete. It has already been pointed out that the time-lag of a thermal relay depends upon the temperature of the sensitive element at the moment of incidence of the excess current, and in the testing of relays of this type not only should the temperature of the air surrounding the relay be recorded, but, before each determination of time-lag, the bimetallic element should be brought to a standard condition. This condition is usually taken as that which obtains when all the relay elements in one case have been carrying the rated full load current for such a time that they have reached a steady thermal condition. Care must, therefore, be taken that after a test, the element is restored to this standard condition before another test with a different value of the relay current is attempted.

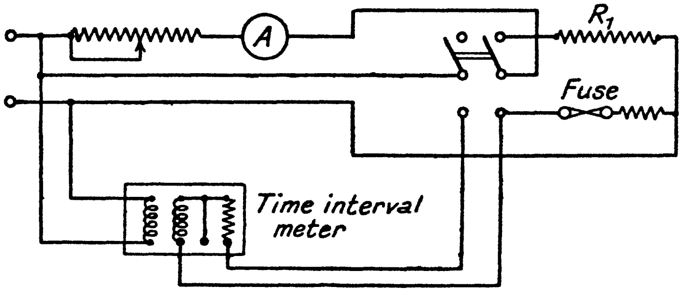


FIG. 199—TEST CIRCUIT FOR TIME LIMIT FUSE.

Over-current relays of the instantaneous and definite time-lag types call for a check of the accuracy of the marked current settings by experimental determination of the minimum currents required to operate the relays. The time settings of definite time relays can be checked by the use of a test circuit such as is shown in Fig. 197. A time/current characteristic for and value of the marked setting should be taken for a range of currents from the minimum to operate the relay to a value at which the time-lag attains its minimum value. The determination of the minimum operating current of a relay is assisted by arranging that the trip circuit contacts switch on an indicating lamp when the operation of the relay is complete. If a moving coil voltmeter is connected in parallel with the relay switch any tendency to chattering at the contacts will be shown by the nature of the movement of the instrument pointer when its reading is extinguished by the operation of the relay.

The testing of under-current and under-voltage relays is quite straightforward and calls for no comment.

Induction over-current relays call for an experimental check of the marked settings, and for the determination of a complete time/current characteristic for one of the marked settings. The accuracy of the time setting scale can be checked by the experimental determination of the time-lag with a constant value of the test current about five times the marked value for several settings of the time scale. The observed time-lags should be in the same ratio as the corresponding settings on the time scale.

Impedance relays are tested in a similar manner to over-current relays with the normal voltage applied to the voltage restraint circuit. A voltage time characteristic can also be taken with a constant value of the relay current, the voltage variation being conveniently obtained by a multi-tap auto-transformer. An experimental impedance time characteristic will, however, be of more practical interest than that connecting time with voltage. This impedance characteristic can be easily obtained by setting up the test circuit so that the relay carries about two to three times the rated full load current, with normal voltage on the voltage restraint coil, and then by means of a multi-tap auto transformer simultaneously reducing the pressure on the current and voltage circuits of the relay. The time-lag of the relay is observed for a number of voltages between the normal value and that which gives the minimum operating current of the relay.

Directional relays are tested for accuracy of the marked current settings with normal voltage on the relay, the relay current being maintained approximately in phase with the relay voltage by the use of non-inductive resistances for the control of the test current. A time current characteristic should be determined for one value of the marked current setting. Voltage compensated directional relays should be tested for minimum operating current at one marked setting for various values of the voltage applied to the voltage circuit down to two per cent. of the rated value. The variation of voltage on the directional relay should be obtained by a multi-tap auto transformer. If series resistance is used, the phase of the current in the voltage circuit may be modified as the applied voltage is reduced, and the wattmeter torque will also be reduced.

The phase error of a directional relay, considered as a wattmeter, can, if this be of the non-compensated type, be readily checked by applying rated current and voltage to the windings, the phase difference between the current and voltage being adjusted to 90 degrees by means of a phase-shifting transformer. When this adjustment is correct, as indicated by a zero reading of a wattmeter excited by the same current and voltage as the relay, there should be no operating torque in the relay. Unless the control on the movement of the relay can be removed for this test it will be difficult to detect a slight torque due to phase error at zero power factor. The test will then be more satisfactory if the current in the relay and wattmeter can be raised to two or three times the rated full load value for the short period necessary for the required observation.

A test for phase error is more difficult to carry out with a voltage compensated directional relay since, with this type, there is an additional control force on the movement due to the unidirectional voltage torque. If the voltage on the relay is reduced to one-fifth of its rated value, the value of the compensating torque will become only 4 per cent. of its normal value, and it may be possible to balance this torque by adjustment of the spring or weight control so that the movement is neutral. If the current in the relay is about four times the rated value, full load volt-amperes at zero power factor will be applied, and any material phase error will be indicated by the presence of a small wattmeter torque on the movement.

Tests on directional relays should include one to verify that there is no tendency to operate with five per cent. voltage and thirty times the setting current in a forward direction as required by the B.S. Specification.

Testing Protective Circuits.—The classes of protective circuits calling for tests on site after assembly and connection are those which include directional and impedance relays, and those in which the relays respond to difference currents and voltages. Directional and impedance relays in three-phase circuits call for tests to verify that the associations of current and voltage in the relays are correct. Differential protective circuits require tests to verify the connections of the protective transformers, and to determine the magnitudes of the stray currents in the relay circuits.

There is no more useful instrument for checking the voltage connections of directional and impedance relays than a single-phase portable power factor meter. The smaller 4-in. and 6-in. sizes give quite sufficient accuracy for this class of test. To check the connections of the voltage circuits of a relay in a circuit-carrying load current, the current coil of the power factor meter is connected in series with the current coil of the relay and the reading of the meter is observed with its voltage circuit connected first to the voltage line terminal corresponding to the line current in the relay and the neutral of the voltage transformer. This reading gives the phase relation of line current and phase volts. The voltage circuit of the power factor meter is then connected in parallel with the voltage circuit of the directional relay. The lag of the current on the voltage should be 30 degrees less than in the first test. The power factor voltage circuit is next joined in parallel with the voltage restraint circuit of the impedance relay, and if this latter circuit is correctly connected the lag of the current on the voltage will be 30 degrees greater than in the first test. The polarity of directional relays is usually checked with great ease by observing the behaviour of the relay when the circuit is transmitting power in a known direction.

The checking of the connections of directional leakage relays is a matter of some difficulty, and when these are energised by a residual current and by a secondary current corresponding to the current in an earthing connection, reliance must usually be placed on a careful examination of the connections between the relay and the current transformers, having regard to the terminal markings of both relay and transformers. If the relay is energised by a residual current and a residual voltage derived from an earthed star open delta voltage transformer bank as shown on p. 63, an electrical check of the correctness of the connections can be obtained by the following method of simulating fault conditions, if the circuit is carrying load. Referring to Fig. 200, if one primary phase winding of the voltage transformer bank is disconnected and short-circuited, a residual voltage will be obtained in the secondary circuit which will be the same as that set up by an earth fault on the line from which the transformer winding was disconnected. If also the current transformers in the other lines are short-circuited and disconnected from the protective circuit, as shown, the current in the relay will correspond to that set up by an earth fault in the line in which the remaining current transformer is situated. The relay is now energised by a residual current and a residual voltage such as would be set up by a leakage current flowing in the same direction as the load current. If, therefore, with the test conditions as shown in the diagram, the flow of power is known to be from the sub-station, the current and voltage in the directional leakage relay should tend to produce operation.

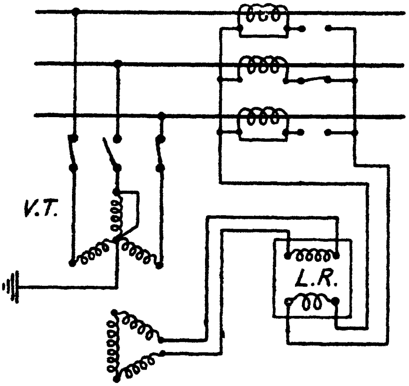


Fig. 200.—Checking Directional Leakage Relay.

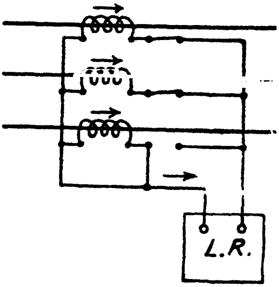


Fig. 201.—Checking Leakage Relay.

The simplest of all differential circuits is that for leakage protection shown in Fig. 201. Provided the current transformers are correctly connected as regards polarity, the only current in the leakage relay, when the circuit is carrying load, is due to inaccuracies of the instrument transformers. If a current transformer secondary is reversed, the current in the leakage relay will correspond to double the line current. The correctness of the current transformer connections is thus readily checked by connecting in the relay circuit an ammeter having a range at least equal to the full load secondary current. The reading of this instrument will be negligible if the current transformers are correctly connected as regards polarity. If the polarity of one of the current transformers is reversed with respect to the other two, the current in the relay branch will correspond to twice the line current. The identity of the reversed transformer can easily be detected by disconnecting one transformer at a time and observing the resulting current in the relay. The two transformers of correct polarity will give a relay current corresponding to the line current. Two transformers, one of which is reversed, will give $\sqrt{3}$ times the line current in the relay. Thus the transformer which is open-circuited while the lower value of the relay current is obtained is the one with reversed polarity. The operation of the protective circuit can be checked by short-circuiting and disconnecting from the circuit each current transformer secondary in turn, in the manner shown in Fig. 201. Each disconnection should divert into the leakage relay a current corresponding to the primary line current.

Care must be taken in the selection of a low reading ammeter for the determination of the stray current in the leakage relay, while the circuit is carrying load. It has already been explained in the course of the discussion of differential circuits, that the magnitude of the current in the difference circuit is largely affected by the impedance of this circuit. To obtain a correct measurement of the stray current in a differential relay, the instrument used should be of negligible impedance, and the higher the impedance of the instrument the lower will be the *apparent value of the stray current. For a given range a milli*-ammeter of the thermo-couple type has the lowest impedance, and, in spite of the disadvantage of the small overload capacity of this type of instrument, it gives the most correct indication of the stray current in the relays of differential protective circuits, and is the most suitable for this test. The rectifier type of milliammeter is the most unsuitable for the measurement of stray currents, due to the fact that the impedance of this type of instrument increases rapidly as the current in it is decreased. This point is illustrated in Fig. 202, which gives the relation between the stray current in the relay of a differential circuit and the relay impedance, and that between the impedance and current of a rectifier milliammeter. Neglecting the relay impedance, the current in the milliammeter is given by the intersection of the two curves. It will be seen that, due to the variable impedance of the instrument the current in the relay circuit may be reduced to about two-thirds of the value that would be given by a milliammeter having a constant impedance of five ohms.

The more complicated differential circuits for generator and transformer protection are checked by a development of the methods used in the case of a circuit for leakage protection. In all cases correctness of the connections is indicated by the presence of very small but appreciable currents in the relay circuits, while the main circuit is carrying load. The rectification of incorrect connections in a complicated protective circuit may be a matter of considerable difficulty and considerable assistance in a problem of this kind can be obtained from a portable power factor meter. With the voltage circuit of this instrument excited from any convenient supply, the secondary currents in the protective circuit can readily be identified and associated by passing them in turn through the current coil of the power factor meter and observing their phase relation to the voltage datum. A degree scale on the instrument is particularly useful for this class of work.

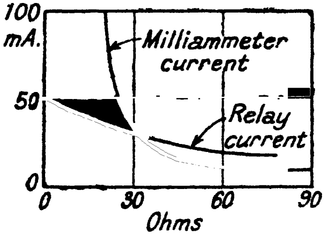


FIG. 202.—CHARACTERISTIC OF RECTIFIER MILLIAMMETER.

As an example of the rectification of an improperly connected protective circuit, we may consider Fig. 203, which shows a Merz-Price circuit for a delta/star transformer in which one of the current transformers in the delta has been connected with wrong polarity while a cyclic change has inadvertently been made in the connection of the circulating current pilots to the star group of current transformers. The errors in the connections would be indicated by currents in the relays of the same order as the secondary currents of the protective transformers when the main circuit is carrying load. The nature of the errors of connection can readily be deduced by short-circuiting the relays and connecting in the pilots on each side

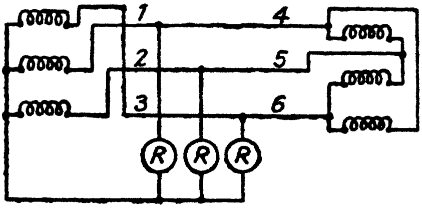


FIG 203—INCORRECTLY CONNECTED MERZ-PRICE CIRCUIT

of the connections to the relays an ammeter and single-phase power factor meter in series, the voltage circuit of the power factor meter being supplied from any convenient source. From the six sets of readings the magnitude and phase of each current are obtained and the vectors of these currents can be drawn. These will be as shown in Fig. 204. The currents from the delta-connected set of transformers are seen to be unequal. One of these currents is equal to each of the currents from the star-connected set, while the other two are each of $\frac{1}{\sqrt{3}}$ times these currents. Faulty connection in the delta is indicated, and the wrongly connected transformer is that from which the smaller currents proceed. Reversing the connections to this transformer, a set of vectors shown by the dotted lines in Fig. 204 is obtained. The values of the currents are now correct, but those proceeding from the delta set of transformers are found, from the indications of the power factor meter, to be lagging 120 degrees on those in corresponding pilot wires from the star-connected set. The necessity of a cyclic change of the pilot wires connected to the star-connected set of transformers is plainly indicated.

Tests on differential protective circuits are much facilitated by the use of a portable link board such as is shown in Fig. 205. This is connected in the circulating current circuit at the point at which the relay tappings are made and the terminal studs are made long enough to accommodate the ends of the pilot wires and also leads to the testing instruments. By the use of such an arrangement, instruments can be connected in the circuit whilst the main conductors are carrying load, without any secondary connections being opened, in the manner shown. The link board is also useful for inserting temporary resistances in the circulating current wiring for experimentally balancing the burdens on the two sets of protective transformers to obtain the minimum stray currents in the relays.

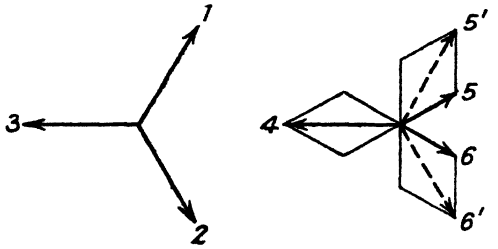


FIG. 204.—VECTOR DIAGRAM FOR CIRCUIT SHOWN IN FIG. 203.

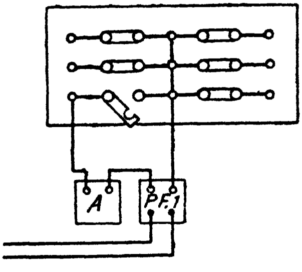


FIG. 205 —TEST TERMINAL BOARD FOR MERZ-PRICE PROTECTIVE CIRCUITS

The measurement of the stray currents in the protective relays of differential protective circuits, whether of the current balance, voltage balance, or split conductor type, should be taken with the same precautions as were explained above in connection with the testing of leakage relays. It is desirable to take three readings of corresponding values of the load current and the relay stray current if possible as, by plotting these sets of values, the rate of increase of the relay current as the load current increases above the rated value can be roughly deduced.

Although the stray relay currents with self-balance and split conductor protective systems are, as a rule, very small when the circuit is carrying normal loads it has recently been pointed out by Arnold that, if the primary conductors are not symmetrically situated with respect to the core, the magnitude of the relay current may become inordinately large with straight-through short-circuit currents. If, therefore, one of a set of relays associated with a protective circuit of one of these types carries a relatively higher stray current than the others, for the same load current, the setting of the primary conductor in the transformer core aperture should be examined.

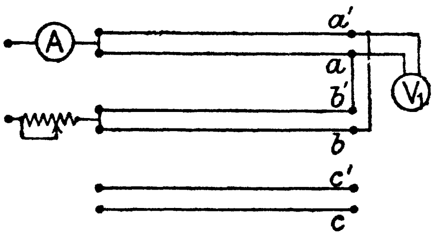


Fig 206 —Checking the Impedance Balance of a Split Conductor Cable

Stray currents in the relays of a split conductor protective system can arise from defective balance of the impedances of the splits as well as from defects in the protective transformers. The impedance balance can be checked by the circuit shown in Fig. 206. Current is passed through two splits in parallel from one end of the cable to the other end and back, the voltage between splits carrying current is observed at the end other than that at which the test current enters and leaves. Readings of the voltmeter are taken with the splits connected as shown, and also with a transposition so that a^1 is connected to b^1 and a to b. With each connection, the reading of the voltmeter should be not more than a fraction of one per cent. of the potential difference between the two ends of the loop.

The complete testing of protective gear includes the passing of test current into the relay windings to ensure that these operate at approximately their rated currents, and also that this operation leads to tripping of the associated oil circuit-breakers. The ability of a relay to open the associated breaker should be tested not only with a current in the neighbourhood of its setting but also with currents considerably exceeding this value. In some solenoid and attracted armature relays of the self-resetting type, chattering of the movement and consequent uncertainty of contact in the trip-circuit switch is more likely to occur with high than with moderate values of the operating current. All such relays, on commissioning, should therefore be tested with a high value of the operating current to ensure that the tripping of the associated breaker is quite certain in this condition. The checking of relays after erection will be dealt with in the next section.

It should be hardly necessary to say that the trip circuit switches of protective relays should not be connected to the oil circuit-breaker operating circuits till the protective circuit has been checked for correctness of connections.

Routine Testing and Maintenance of Protective Gear.—Although protective gear may be correctly assembled, it cannot be expected to perform its duties satisfactorily and reliably unless it is periodically tested and overhauled. Modern relays are relatively delicate in construction and partake generally of the nature of electrical instruments. An electrical instrument differs from a relay in that it is normally in active service; a defect which occurs in an instrument is usually readily detected, and, generally, such a defect has no serious consequences. A relay, on the other hand, only operates in exceptional circumstances, and very rarely, and any failure to operate when it should, is attended by serious consequences. For this reason the artificial electrical operation of all protective relays at regular intervals, not exceeding one month, is essential in order that defects in the relay or in the wiring thereto may be promptly detected and rectified. The artificial operation of protective relays should, in all cases, include the automatic tripping of the associated circuit-breaker.

The artificial operation of relays for testing and checking purposes should be carried out by a simulation of fault conditions in the primary circuit protected by the relay, and the closest simulation of this condition is given by the passage of current in the primary winding of one of the current transformers from which the relay is energised. This method of testing calls for the provision of a portable transformer capable of delivering heavy currents. An equipment for testing according to this method is bulky, and not readily transportable, while the method is only applicable to those types of switchgear in which the primary conductors are readily accessible. Most modern switchgear equipments are of the armour-clad type in which the primary conductors are compound or oil-immersed, and, with such gear, it is seldom practicable to pass testing current into the primary windings of the protective transformers. It has been suggested by Wellings and Mayo that protective transformers installed in armour-clad gear be provided with a third winding, which, for testing purposes, would be used as an alternative primary. The number of turns on the alternative primary could be approximately equal to that of the secondary turns so that the full rated primary current could be obtained from a test equipment of moderate size. The provision of these auxiliary windings would be most advantageous from the point of view of the testing of protective gear as fault conditions could be simulated completely and with ease. The auxiliary windings might introduce a slight possibility of danger, if used with transformers for differential protection, since an accidental short-circuiting of these windings, in conditions of normal loading, would cause the auxiliary winding to behave as an alternative secondary circuit, so that current would be diverted from the main secondary circuit, and the conditions would correspond to that of a fault in the main circuit. It would therefore be necessary to locate the terminals of the auxiliary testing windings in a sealed enclosure, accessible only to the staff responsible for relay testing.

If testing current cannot be applied to the main primary conductors or to a special primary winding of the protective transformers, the relays must be tested with current passed directly into the secondary circuit. A consideration of the equivalent circuit of a current transformer shown in Fig. 18

will show that the operation of a protective relay in terms of primary current can be very approximately determined by connecting the leads from the source of test current directly to the terminals of the current transformer which supplies the relay. A more convenient procedure is to connect these leads to the terminals of the relay under test. This decreases the virtual burden on the current transformer, since the connecting leads only carry the exciting current, but, unless the transformer is located a considerable distance from the relay, this circumstance will not greatly affect the accuracy of the test. If the source of test current is derived from a low voltage supply with an earthed neutral, the arrangement of the test circuit

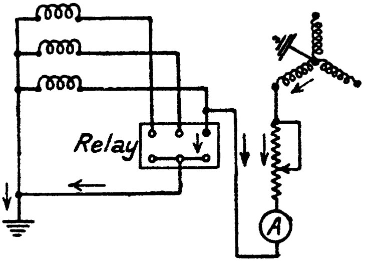


FIG. 207.—METHOD OF TESTING OVERCURRENT RELAYS ON SITE.

will be as shown diagrammatically in Fig. 207. It will be seen that one test lead only is required, and that none of the permanent connections to the relay need be disturbed.

If the secondary network includes a residual-current or earth-leakage relay, this relay can be similarly tested.

The arrangement of Fig. 207, in which testing current is derived directly from the supply mains will only simulate line-to-earth faults in a 3-phase protective system. When a step-down transformer is used as a source of testing current, single-phase faults between lines can be simulated by connecting the transformer to the corresponding terminals of two current transformers or relay elements, so that the greater part of this current passes through the two elements in series. Casson and Birch have described an arrangement of two step-down transformers, supplied on the primary side through phase-shifting transformers whereby any kind of fault can be simulated in a 3-phase protective network. Details of this arrangement will be found in a paper to which reference is made in the Appendix.

The testing of relays by passing current into them with their associated current transformers remaining connected in the normal way, whether this current is derived directly from the supply mains or from a step-down transformer is now often called the secondary-injection method. In each case the actual primary current required to operate the relay is approximately equal to the observed value of the injected current required to cause operation multiplied by the ratio of the current transformer to which the relay is connected. The secondary injection method, it should be noted, is essentially one for the determination of fault-current operating values; excepting when the relay impedance is very low it will not accurately determine the actual relay operating current, as the shunting effect of the transformer secondaries connected to the relay during the test corresponds to the effect of the errors of the transformers in fault-operating conditions. If it is desired, for any reason, to check the marked secondary operating current of a protective relay on site, the relay should be disconnected from the secondary network.

When the transformers for self-balance or core balance leakage protective gear are unenclosed and are placed over lead sheathed cables, this class of gear can very conveniently be tested by passing the test current through a length of the lead sheath which passes through the transformer core aperture. This procedure is often convenient for Merz-Price protective gear for turbo-alternators, the test current being passed into the sheaths of the cables forming the neutral point connection of the alternator.

Split conductor protective gear is readily tested by passing current into a loop formed of the two splits of one phase. As the test current passes twice through the core aperture of the protective transformer, the effective value of the artificial fault current is twice that of the test current.

Timing tests on protective gear can be arranged to measure the inherent time-lag of the relay, the combined time-lag of the relay and the circuit-breaker tripping time, or the circuit-breaker and relay times separately. Fig. 208 gives the connections of a circuit for measuring the inherent time-lag of a relay. It will be seen that the clutch coil of the time interval meter is energised from the control supply for the switchgear operation. This supply is switched on to the clutch coil circuit simultaneously with that of the test current to the relay. The clutch coil of the time interval meter is short-circuited by the relay switch on the completion of the travel of the movement.

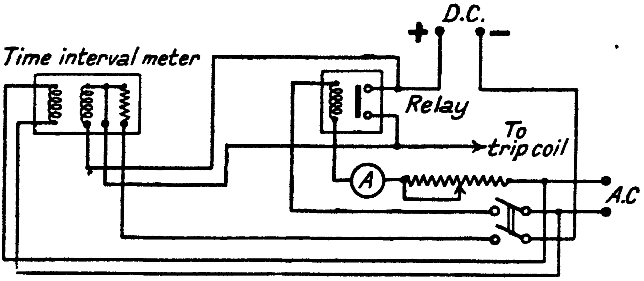


FIG. 208.—TIMING AN OVERCURRENT RELAY.

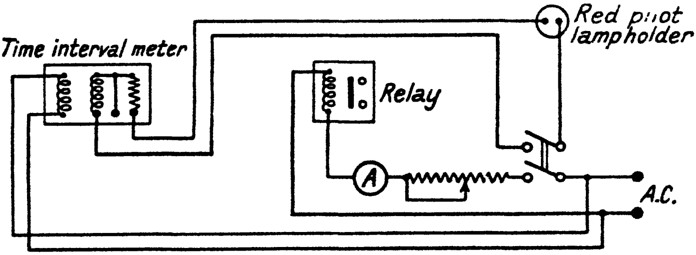


FIG. 209.—OBTAINING THE COMBINED TIME-LAG OF A RELAY AND CIRCUIT BREAKER.

Fig. 209 gives the connections of a convenient circuit whereby the overall time of the relay and breaker are directly observed. The clutch coil circuit is energised from the lamp holder for the red pilot light at the same instant that the test current is passed into the relay windings. The opening of the circuit-breaker interrupts the supply to the red pilot lamp and de-energises the clutch coil.

Fig. 210 gives the connections of a circuit for testing the discriminating margin given by relays in neighbouring sub-stations having different nominal time-lags. The testing equipment is located in the sub-station having the relay with the smaller time-lag. Testing current is passed, via one core of an interconnector from a live terminal of the local low pressure supply through the two relays in series to earth. An independent circuit contains the clutch coil of the time interval meter. It will be seen that this circuit is so arranged that the operation of the relay R_1 and the opening of the associated breaker removes the short-circuit of the clutch coil. The operation of the relay R_2 de-energises the clutch coil. When, therefore, the testing current is switched on to the relay circuit, the clutch of the timing motor is not energised till relay R_1 has operated. The time interval motor then registers till the operation of R_2 and the interruption of the supply to the clutch coil. The reading of the meter thus gives the time interval between the operation of the two relays.

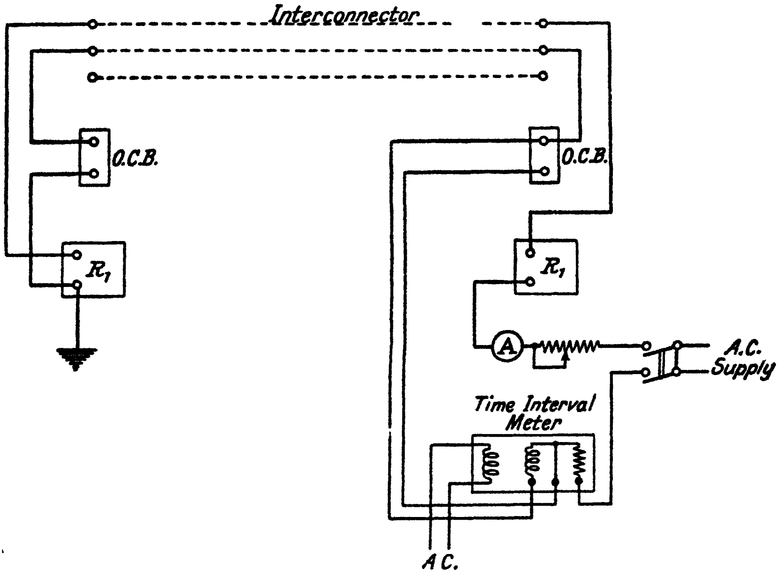


FIG. 210—TIME SEQUENCE TESTING OF RELAYS

The use of the time interval meter for the direct measurement of the opening and closing times of a circuit-breaker is so simple as not to require detailed explanation. The connections can conveniently be arranged so that the clutch coil is energised by the operation of the controller and opened or short-circuited by the breaker as the case may be.

Routine monthly tests to check the ability of protective gear to operate need not be of a quantitative character. These tests will usually be carried out by the operating staffs of the power-station and sub-stations in which the protective gear is installed, and they should be of the simplest character, consisting merely in the passage of a current through the relay windings considerably in excess of its minimum operating current. The resistances for these tests should be made up permanently, so that no adjustment is required. The test then consists merely in attaching the test lead to the relay terminal, switching on the supply, and observing that the breaker trips. For relays with an inverse time-lag the value of the test resistance should be such that the approximate time-lag is approximately constant, a convenient nominally standard value being one second.

At less frequent, but periodical intervals, all protective relays must be overhauled and tested by a competent and properly trained staff. These tests will cover the checking of the minimum operating current, and of the time'current characteristics of the relay. They need not be so complete as the original laboratory tests, but they should be sufficient to ensure that the characteristics as originally determined have not materially changed.

An item of great importance in the maintenance of pilot wire protective systems for cables is that of the periodical testing of the pilots for insulation and continuity.

Records of Relay Tests and Performance.—The results of tests on protective apparatus should be recorded, according to a carefully planned system, and preferably on a printed form. Whether tests for operation are conducted by operating staffs, or calibration and timing tests are carried out by the relay maintenance staff, the result of each individual test should be separately recorded, and the record form should be so designed that an entry corresponding to each test is definitely called for. Forms designed on these lines prevent essential tests being omitted as they constitute a permanent instruction to the tester. Further, a well-designed form facilitates the scrutiny of the test results by the supervising engineer. It is generally desirable to provide spaces for entries of the results of tests of a non-quantitative nature, and of the results of routine essential inspections. Even for tests of the simple character described on p. 296, in which a current is merely passed through a relay to operate it the form should contain a space for an entry corresponding to the checking of each relay element.

Of equal importance to the recording of the results of relay tests is that of the keeping of a full and clear account of the operation of relays in fault conditions Modern protective gear is still fallible, and faulty performance may consist either in failure to isolate a faulty machine or circuit or the improper operation of a relay controlling a circuit which is not defective. As soon as possible after a fault which causes relay operation, the fullest relevant technical particulars should be collected by an engineer specially charged with this duty. These particulars, together with particulars of any special investigations and tests carried out to trace the cause of improper relay operation, whether these tests are successful or not, should be clearly recorded in a permanent log It is possible to devise a form for the recording of relay operations, and a specimen form will be found in the E.R.A. Report, "Statistical Survey of the Performance of Automatic Protective Systems," referred to in Appendix I to this book. Otherwise, and perhaps preferably, the record can be made in the form of a report. It will generally be desirable to prepare yearly a statistical record of all relay operations, correct and incorrect. The conscientious keeping of an account of relay performance is of great value, not only because it enables the efficacy and reliability of any particular type of relay or protective scheme fairly to be assessed after a period of service, but also because the causes of faulty relay operation can be traced the more easily if a full and complete history of the previous performance of the relay is available.

APPENDIX I

RECENT WORKS AND PAPERS DEALING WITH PROTECTIVE GEAR AND APPARATUS

1. " Protective Apparatus for Turbo Generators," by J. A. Kuyser, *Journal, I.E.E.*, 1922, Vol. 60, p. 761. Contains a useful discussion of field suppression.

2. " The Design of Apparatus for the Protection of Alternating Current Circuits," by A. S. FitzGerald, *Journal, I.E.E.*, 1924, Vol. 62, p. 561. Describes fully the biasing transformer and its applications.

3. *Electrical Transmission and Distribution*, Vol. 4. " Protective Systems for A.C. Mains," by B. H. Leeson, 1929. A good general survey of modern practice.

4. " Instrument Transformers," by J. G. Wellings and C. G. Mayo, *Journal, I.E.E.*, 1930, Vol. 68, p. 704. An excellent paper containing much useful information relating to protective transformers.

5. " Recent Developments in the Protection of Three-phase Transmission Lines and Feeders," by T. W. Ross and H. C. Bell, *Journal, I.E.E.*, 1930, Vol. 68, p. 801. A paper devoted mainly but not exclusively to relays of Metropolitan-Vickers manufacture, and which deals with D.C. pilot wire protective circuits.

6. " The Protection of Parallel Feeders, Interconnectors and Transformers," by W. Wilson, *World Power*, 1930, Vol. 15, p. 371 *et seq.* Describes fully the applications of the biased beam relay.

7. " The Testing of Protective Current Transformers," by W. Wilson, *World Power*, 1931, Vol. 15, p. 371. A useful and practical paper.

8. " Some Recent Advances in the Design of Relays for the Protection of A.C. Circuits," by C. L. Lipman, *Journal, I.E.E.*, 1932, Vol. 71, p. 561. Deals exclusively and in great detail with relays of Nalder Bros. and Thompson manufacture.

9. " Faults and their Clearance on Large Networks," by R. O. Kapp and C. G. Carrothers, *Journal, I.E.E.*, 1932, Vol. 71, p. 685. An excellent paper containing a penetrating discussion of the problem of distance protection.

10. *Symmetrical Components*, by C. F. Wagner and R. D. Evans, 1933. An authoritative and comprehensive work dealing with the theory of symmetrical components and its application to network calculations.

11. *Symmetrical Component Analyses of Unsymmetrical Polyphase Systems*, by R Neumann. 1939. A work similar in scope, but simpler in character than the foregoing.

12. *Automatic Protective Gear for A.C. Supply Systems*, by J. Henderson, 1934. A good descriptive review of modern practice.

13. *Relay Systems*, by I. T. Monseth and P. H Robinson, 1935. A comprehensive treatise dealing exhaustively with American relays and protective systems and with the theory and practice of network calculations

14. "Statistical Survey of the Performance of Automatic Protective Systems" (*E.R.A Report* F/T94), *Journal, I.E.E.*, 1936, Vol. 79, p. 541. This Report contains a critical discussion of relay failures.

15 *Capacitor Voltage Transformers*, by Wellings, Mortlock and Mathews. *Ibid.* p. 577. Deals fully with theory, testing, construction and applications.

16. "Bus-Bar Zone Protection," by T. W. Ross. *Metropolitan-Vickers Gazette*, 1936, Vol. XVI, p. 266. An excellent study of available methods.

17. *N.E.L.A. Relay Handbook and Supplement.* A manual dealing exhaustively with American relays and with the technique of routine testing and maintenance.

18. "Neutral Inversion in Power Systems," by B. G. Gates, *Journal, I.E.E* , 1936, Vol 78, p. 317. Contains a full discussion of this phenomenon

19 "Safeguards against Interruptions of Supply," by H. W. Clothier B. H. Leeson and H. Leybourn *Journal, I E.E.*, 1938, Vol 82, p. 445 Describes some recent developments in protection technique.

20. "High-Speed Protection as an aid to maintaining Electro Service following System Short-Circuits," by T. W. Ross and C. Ryder, *Journal, I.E.E.*, 1938, Vol. 88, p. 228. A critical review of modern developments in this field.

21. "Applications and Limitations of Inverse-Time Overload Relays to the Protection of an 11kV Network," by J. W. Gallop and R. H. Bousfield, *Journal, I.E.E.*, 1940, Vol. 87, p. 113. A detailed description of the application of the graded time-lag system of feeder and interconnector protection.

22. "Maintenance of Relays and Associated Equipment," by J.

R. Brookman, *Journal, I.E.E.*, 1940, Vol. 87, p. 485. Describes the maintenance system used for a large protective scheme in South Australia.

23. " Improved Timing Device," by R. B. Rowson, *Electrical Times*, 1941, Vol. 101, p. 30. Describes the construction of a home-made time-interval meter for relay testing.

24. " Selection and Maintenance of Relay Contacts," by G. Windred, *Electrical Times*, 1941, Vol. 100, p. 235. An excellent and critical review.

25. " The Management of Protective Gear Systems on Power Supply Systems," by W. Casson and F. H. Birch, *Journal, I.E.E.*, 1942. An exhaustive discussion of the calculation of fault-currents and the performance, commissioning and maintenance of the protective gear used by the C.E.B.

APPENDIX II

GLOSSARY OF TECHNICAL TERMS RELATING TO PROTECTIVE GEAR

Air Gap Current Transformer. A current transformer the magnetic circuit of which contains an air gap so that the open circuit secondary E.M.F. is sensibly proportional to the primary current.

Ampere-Turns. The product of the number expressing the full load current in amperes by the number of primary turns in a current transformer is known as the ampere turns.

Attracted Armature Relay. A relay consisting essentially of a pivoted iron armature and an electro-magnet.

Auxiliary Relay. A relay actuated from a separate source of supply by the main relays, and which closes the trip circuit of an oil circuit-breaker.

Auxiliary Switch. A switch coupled mechanically to an oil circuit-breaker which opens circuit or closes circuit when the associated breaker opens.

Back-up Protection. A system of over-current relays with high current and time settings intended to operate only in the event of a failure of the main relays.

Beam Relay. A relay consisting essentially of a pivoted beam responsive to the difference of the forces of two solenoids on their associated plungers.

Bias. A device whereby the current required to operate a relay in a differential protective circuit depends upon the magnitude of the current in the main circuit.

Biasing Transformer. A current transformer whose ratio of secondary to primary current decreases as the current in a tertiary or biasing winding increases.

Breakdown of Ratio. The ratio of a current transformer is said to break down when, due to magnetic saturation of the core, the value of the secondary current differs considerably from its nominal value.

Burden. The burden of an instrument transformer may be:
(*a*) The instruments, relays, and connections forming the secondary circuit.
(*b*) The impedance of the secondary circuit in ohms.
(*c*) The volt-amperes absorbed by the secondary circuit when the primary current or voltage has its rated value.

Bushing Current Transformer. A current transformer without a primary winding.

Circuit-Closing Relay. A relay in which the contacts are normally open.

Circuit-Opening Relay. A relay in which the contacts are normally closed.

Circulating Current. The current which in a differential protective circuit flows in the direct circuit between the current transformers.

Closing Coil. (*a*) Of a contactor The coil which holds the contactor in the closed position.
(*b*) Of an oil circuit-breaker. The coil which closes the breaker, but which is de-energised when the movement is completed

Compensated Pilot. A pilot cable in which the insulated cores are surrounded by metallic sheaths which provide paths for the capacitance currents.

Core Balance Transformer. A current transformer whose primary consists of the three conductors of a three-phase circuit.

Cross-connected Current Transformers. The series connection of the secondary circuits of current transformers whose primary circuits are normally equal.

Definite Impedance Relay. A relay which acts with a constant ratio of voltage to current.

Definite Minimum Time-lag. A time-lag which for high values of the operating current assumes a constant value.

Definite Time-lag. A time-lag which is nominally independent of the current or power in the relay.

Delta Connection. The series connection of three-current or voltage transformers in a three-phase circuit.

Differential Protection. A method of protection whereby the protective relays are responsive to differences of the currents in the primary circuits of the current transformers.

Directional Relay. A relay which responds only when the power flow in the associated circuit is in a specified direction.

Discrimination. The property of a protective circuit whereby the relay responds only to faults in the section of the main system which it controls.

Distance Protection. A system of relays whose essential property is that the relay nearest to a fault operates with the smallest time-lag.

Diverter Relay. An auxiliary relay which modifies the setting of an associate drelay

Drop-off Current or Voltage. The maximum value of the current or voltage which will cause operation of an under-current or an under-voltage relay.

Drop Switch. A relay switch which falls by gravity into the closed position when the relay operates.

Dynamometer Relay. A relay consisting essentially of a pivoted coil moving in the field of an electro-magnet.

Encroachment. The approach of the value of the stray current (q.v.) in a relay to the value required for operation, as the value of the straight-through current in the main circuit tends to its maximum value.

False Trip. The operation of a relay and the tripping of i associated breaker by causes other than that of a fault in t section controlled.

Graded Time-lags. A method of adjusting the time-lags of relays whereby their magnitude depends upon the distance of the relay from the source of supply.

Ground Fault Protection. See " Leakage Protection."

Ground Fault Relay. See " Leakage Relay."

Hand-Resetting Contacts. Relay contacts which after operation of the relay have to be restored to their normal position by hand.

Healthy Circuit. A circuit, or section of a transmission system, which contains no fault, notwithstanding it may be carrying the fault current of another section.

High-Speed Relay. A relay of which the operating time is of the order of a few cycles.

Impedance-time Relay. A relay whose time-lag depends upon the ratio of voltage to current.

Induction Relay. A relay consisting essentially of a pivoted member moving in the field of an electro-magnet and in which currents are induced.

Instantaneous Relay. A relay in which the time-lag is designed to be as small as possible.

Inverse Time Relay. A relay in which the time-lag decreases as the value of the operating current or power increases.

Kick Fuses. Fuses shunting the relays of a differential circuit for transformer protection, to prevent the operation of the relays by the transient current surge at the switching-in of the transformer.

Leakage Protection. A system of protection depending upon the use of leakage relays.

Leakage Relay. A relay responsive only to earth fault currents in a three-phase circuit.

Margin of Stability. The difference between the maximum value of the current which can appear in a relay when no fault exists in the circuit controlled and that required to operate it.

Merz-Beard Protection. A system of protection employing current transformers with two primary windings which normally carry currents which are equal and opposed.

Merz-Hunter Protection. A system of cable protection in which double-primary current transformers carry the normally equal currents in two parallel circuits.

Merz-Price Protection. A system of protection whereby the relays are responsive to differences of the secondary currents or voltages of current transformers whose primaries carry currents which are normally equal.

Mesh Connection. See " Delta Connection."

Moving Iron Relay. A relay consisting essentially of a pivoted iron vane moving in the field of an electro-magnet.

Mumetal. An alloy of nickel and iron which has its maximum permeability for abnormally small magnetising forces.

Negative Sequence. A negative sequence component is that symmetrical component of an unbalanced system of three-phase vectors whose phase sequence is opposite to that of the resultant system.

Negative Sequence Relay. A relay responsive to negative sequence current, voltage, or power.

Neutral. The common connection of three circuits connected in star in a three-phase supply.

Neutral Inversion. An abnormal condition in which the point representing earth potential lies outside the triangle of the vectors of line-voltages of a 3-phase system

Ninety-Degree Connection. A method of connecting single-phase directional relays in a three-phase circuit whereby the associated currents and voltages are in phase quadrature with a balanced power factor of unity.

Non-Directional Relay. A relay whose operation does not depend upon the direction of power flow in the circuit it controls.

Open-Delta Connection. The series connection of two voltage transformers in a three-phase circuit.

Opposed Voltage Protection. A method of protection in which are compared the secondary voltages of current transformers whose primaries carry currents which are normally equal.

Over-current Relay. A relay intended to operate when the current in the circuit controlled exceeds a stipulated value.

Overload Relay. See ' Over-current Relay."

Over-speed Relay. A relay intended to interrupt the supply to a machine when its speed exceeds a stipulated value.

Over-voltage Relay. A relay intended to operate when the voltage in the circuit controlled exceeds a stipulated value.

Phase Balance Relay. A relay which is intended to operate when the unbalance of the currents in a three phase circuit exceeds a stipulated amount.

Phase Fault. A fault involving a short-circuit between the lines of a three-phase system.

Phase Sequence. The sequence in which the line-to-neutral voltages of a three-phase system attain their positive maximum values.

Pick-up Current or Voltage. The minimum current or voltage which will give rise to operation of an over-current or an over-voltage relay.

Positive Sequence. A positive sequence component is that symmetrical component of an unbalanced system of three-phase vectors whose phase sequence is the same as that of the resultant system.

Ratio Balance Relay. A relay so designed that operation takes place when the ratio of two electrical quantities assumes a stipulated value.

Reactive Relay. A name sometimes given to an ironclad dynamometer relay.

Reinforcing Coil. An electro-magnet which increases the force closing the relay contacts after operation.

Release. The operation of a relay and the tripping of the associated oil circuit-breaker.

Residual Current. The vector resultant of the three line currents of a three-phase system.

Residual Voltage. The vector resultant of the three line-to-earth voltages of a three-phase system.

Restraint. See " Bias."

Reverse Current Relay. A directional relay responsive to a value of the current which is unaffected by large voltage variations.

Reverse Phase Relay. A relay designed to operate if the phase sequence of the controlled circuit is reversed.

Reverse Power Relay. A directional relay responsive to a stipulated value of the power in the circuit controlled.

Saturation. The condition of a magnetic circuit in which an increase in the magnetising force causes a relatively small increase in the flux density.

Saturation Transformer. A current transformer so designed that the secondary current is sensibly constant for primary currents exceeding a stipulated value.

Screened Pilot. See " Compensated Pilot."

Selectivity. See " Discrimination."

Self-balance Protection. See " Merz-Beard Protection."

Self Braking. The dynamic braking torque on a relay movement due to its rotation in the flux which sets up the driving torque.

Self-Resetting Contacts. Relay contacts which after operation return automatically to their normal position.

Series Tripping. The use of the secondary current of a protective current transformer to trip an associated circuit-breaker.

Setting. The adjustment of a relay which determines the operating current, voltage, or impedance, or the time-lag.

Shaded Pole Relay. A type of induction relay in which a phase difference of two alternating fluxes is produced by a copper band encircling a portion of a pole piece of the electro-magnet producing these fluxes.

Short-circuit Time-lag. See " Definite Minimum Time-lag."

Shunt Tripping. The use of an independent source of supply (usually direct current) for the tripping of a circuit-breaker.

Slow Resetting Relay. A relay in which the self-resetting action is intentionally delayed till the lapse of a considerable time after the cessation of the operating current.

Solenoid Relay. A relay consisting essentially of a plunger moving in a solenoid.

Spill Current. In a differential protective circuit, the secondary current, corresponding to the difference of the primary currents, which passes into the relay.

Split Conductor Protection. See "Merz-Hunter Protection."

Split Pilot Protection. The application of the split conductor principle to the secondary circuit of a differential protective system.

Stability. The property of a protective circuit whereby it is unaffected by currents due to faults external to the section it controls.

Stability Ratio. The ratio of the current required to operate a relay to the maximum current which can appear in it when no fault exists in the circuit it controls.

Star Connection. The parallel connection of three-current or voltage transformers in a three-phase circuit.

Straight-through Current. The current in a section of a transmission network due to a short-circuit or earth fault external to it.

Stray Current. The current in a relay connected in a differential circuit, due to inaccuracies of the protective current transformers, and not to a fault in the section controlled.

Summation Transformer. A current transformer whose secondary current is proportional to the vector sum of the currents in its several primary windings.

Thermal Relay. A relay whose action essentially depends upon the heating effect of the current it carries.

Thirty-degree Connection. A method of connecting the voltage circuits of single-phase directional relays in a three-phase circuit whereby the relay voltage leads in phase by 30 degrees on the relay current when the three-phase power factor is unity and the load is balanced.

Time-lag. The time-lag of a relay is the interval elapsing between the incidence of the operating current and the closing or opening of its contacts.

Transfer Relay. A relay which, on the incidence of an earth fault, modifies the connections of an impedance relay.

Transient. An electrical condition in a circuit which does not persist for more than one or two cycles.

Translay Relay. A combination of relay and transformer in which operation of the relay depends upon the flow of current in a secondary circuit.

Trip Coil. The electro-magnet which trips the hold-in latch of an oil circuit-breaker.

Tripping Relay. See "Auxiliary Relay."

Tuned Relay. A relay which is so designed as to respond only to a current whose frequency approximates to a stipulated value.

Turns Compensation. A method of partial compensation for the ratio error of a current transformer by the use of a number of secondary turns less than that corresponding to the nominal ratio.

Turns Ratio. The ratio of the number of secondary turns to the number of primary turns in an instrument transformer.

V Connection. See "Open Delta Connection."

Vector Unbalancing. The difference current in a protective circuit due to a difference in phase of two secondary currents of equal magnitudes.

Voltage Compensated Relay. A directional relay so designed that the operating current is very little affected by large changes of voltage.

Volt-ampere Consumption. (a) The product of the number expressing the rated current of a relay or instrument in amperes into the number expressing the voltage drop when this current is passing. (b) The product of the number expressing the rated voltage of a relay or instrument into the number expressing the current in amperes when this voltage is applied.

Y Connection. See "Star Connection."

Z Connection. A combination of the delta and star methods of connecting current transformer secondaries whereby two over-current relays are responsive to short-circuits between any two pairs of lines of a three-phase circuit.

Zero Sequence Component. The symmetrical component of an unbalanced system of three-phase vectors with a resultant, all three members of which are in phase. The magnitude of a residual current or voltage (q.v.) is three times that of the corresponding zero-sequence component.

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